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Urbanization and small household agricultural land use choices in the Brazilian Amazon and the role for the water chemistry of small streams

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Many small watersheds and streams in the Brazilian Amazon have been impacted by agriculture and urban development, often due to household economic needs and migration processes. This study examined the relationships between land use, soil type, and household factors on stream water chemistry in and near the city of Altamira, Pará, Brazil, in 2008–2009. While soil weathering and stream discharge may have affected several stream water ion concentrations, agriculture and especially urban development were associated with high dissolved nitrogen concentrations, high water temperatures, and low dissolved oxygen concentrations in streams. Younger interviewed households were generally associated with these watersheds, and many urban residents reported disposing of household waste directly into streams. In contrast, older households were generally associated with forest and cocoa agriculture, along with lower water temperatures and higher dissolved oxygen concentrations in streams. These conditions persisted despite reported uses of herbicides and fertilizers by some residents.

Keywords: Amazon; land cover change; streams; water quality; urbanization

1. Introduction

In many parts of the Amazon Basin, agricultural development and urban expansion have dramatically altered the composition of land cover in watersheds, especially small catchments (Keller, Bustamante, Gash, & Dias, 2009). Such land use and development activities have been shown to profoundly impact the water balance and biogeochemical cycling of solutes in stream water, including increased dissolved calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), sodium (Na^{+}), chloride (Cl^{-}), and phosphate (PO_4^{3-}) (Deegan et al., 2010; Figueiredo et al., 2010; Markewitz et al., 2011; Neill et al., 2011).

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Development in these small catchments is particularly significant for the transfer of nutrients and organic matter, as small streams have been found to play a large role in the transport of nutrients from catchments (Peterson et al., 2001).

Often, development in the Amazon has produced highly heterogeneous landscapes comprised of a patchwork of different land cover and land use types, including forest regrowth and remnant forest areas, pasture, agriculture and agroforestry systems, and different degrees of urban development (Browder, Wynne, & Pedlowski, 2005; Moran, Brondizio, & McCracken, 2002). Such diverse landscapes within watersheds are expected to have unique and varying impacts on the water chemistry of small streams draining them (e.g., Figueiredo et al., 2010). Further, only a few studies have considered stream water quality in urban Amazonian streams (Couceiro, Hamada, Luz, Forsberg, & Pimentel, 2007; Primo dos Santos, 1997; Sousa, Salimon, Figueiredo, & Krusche, 2011), and all of those studies have generally focused on catchments draining very large urban areas; in the Amazon, urbanization has taken on a variety of forms, from large urban capitals to regional centers (such as the city of Altamira in the study area) and smaller clusters of households in rural areas known as *agrovilas* (Moran, 1981).

One of the key drivers of landscape changes in the Amazon has been land use decisions by households, particularly where, when, why, and how to use an area of land. Several studies have shown that factors associated with households, particularly a household's stage in the household life cycle, can play an important role in how and why agricultural decisions are made, such as expanding an area of agricultural production to meet household needs (Brondizio et al., 2009; Browder et al., 2008; Moran, Brondizio, & VanWey, 2005; Soler, Verburg, & Alves, 2014; Walker, DeFries, Del Carmen Vera Diaz, Shimabukuro, & Venturieri, 2009). While these studies largely have focused on how household decisions affect the amount and distribution of land cover, what is relatively understudied is how household activities relate to streams, particularly stream water chemistry, though several studies have noted the importance of streams and rivers for household and agricultural uses, such as food, drinking water, aquaculture, and water sources for cattle (McClain & Cossío, 2003; Moran, 1993). Understanding the impacts to stream water quality from household decisions about land and water use (including from households in urban areas) is particularly important because the livelihoods of local residents are, in many ways, dependent on or affected by the movement of water in the region, including rainfall, stream and river flow, and use of aquatic resources. This concern is amplified in light of climate change scenarios that highlight more drought and extreme weather events (e.g., Phillips, 2010).

The objective of this work, then, was to identify the relationships between household demographic patterns, land use and urban development in watersheds, and the water chemistry of small streams draining those catchments. It was hypothesized that areas with extensive agriculture and urban development within a watershed would correspond with decreased stream water quality (e.g., higher concentrations of some cations and anions in stream water, such as ammonium (NH_4^+), Na^+, Cl^-, along with increased water temperature and decreased dissolved oxygen (DO) concentrations). Because of greater economic and development needs, younger households were thought to be more associated with these watersheds, as they required faster monetary gains to sustain their growth (e.g., through cattle ranching or working in business in urban areas).

2. Methods

2.1. Study area and watershed selection

This research was conducted in 25 watersheds in and near Altamira, in the state of Pará, Brazil (Figure 1). Nearly 4000 rural lots approximately 100 hectares in size are situated along the Transamazon Highway (BR-230) from Altamira to beyond the municipal seat of Medicilândia (this area also includes the city of Brasil Novo). The residential population in this area greatly expanded since the 1970s following construction of the highway as part of a national settlement plan led by the Brazilian National Institute for Colonization and Agrarian Reform (Moran, 1981). At the time of study, the municipalities of Altamira, Brasil Novo, and Medicilândia (in which the cities reside) contained approximately 90,068, 6912, and 9622 total residents, respectively (IBGE, 2010).

Prior to fieldwork, watersheds with a minimum catchment area of 1.5 km^2 were delineated for the entire study area using the ArcHydro Tools 1.4 toolset for ArcGIS 9.3 (ESRI, Redlands, CA), a 30 m digital elevation model (USGS, 2008), and a spatial data set of stream locations digitized from a 1:100,000 scale topographic map from the Brazilian Institute of Geography and Statistics (IBGE) (IBGE, 2008). A randomly selected spatial sample of 25 watersheds of varying sizes and land cover and stratified by distance to the Altamira road network (especially BR-230) was determined from initial site selection (Cak, 2011). Stream sample sites (e.g., the watershed outflow point) were located using a global positioning system device.

2.2. Identifying land cover and soils in watersheds

A Landsat 5 Thematic Mapper (TM) image was acquired in the dry season of 2008 for analysis. Following radiometric and atmospheric calibration with the dark-object subtraction method (Green, Schweik, & Randolph, 2005; Li, Lu, Moran, & Hetrick, 2011), this image was geometrically registered to a previously rectified Landsat TM image with a

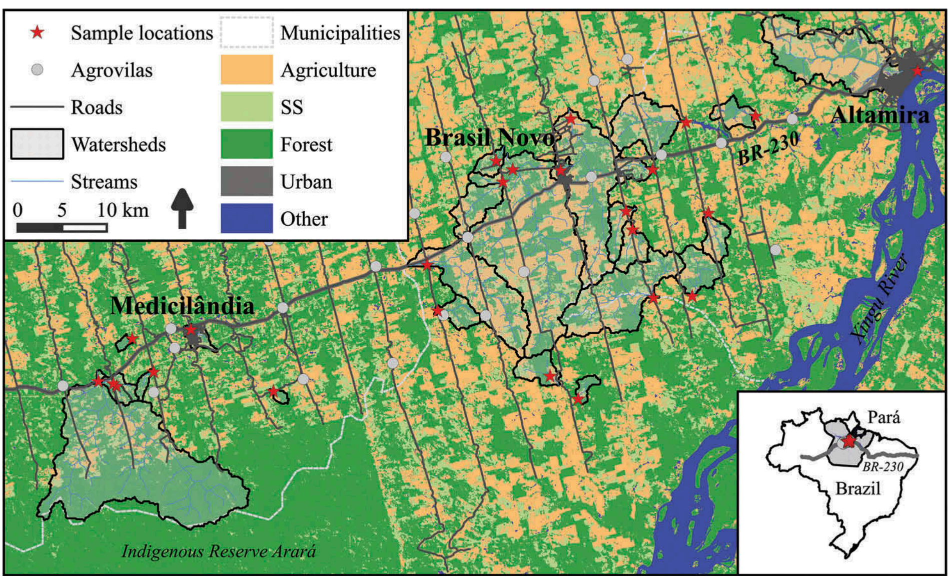

Figure 1. Study area near Altamira, Brazil.

root mean square error of less than 0.5 pixels. Maximum likelihood classification was used to generate the following initial land cover classes: forest, three succession stages (initial (SS1) – forest regrowth with an average stand height of less than 6 m; intermediate (SS2) – forest regrowth with an average height of 7–15 m; and advanced (SS3) – forest regrowth with an average height above 15 m), pasture, burned areas, impervious surfaces (i.e., urban areas with paved and dirt roads, buildings of variable size and shape, and other infrastructure and cleared space, akin to both urban and suburban development in many parts of the world), wetlands, and water. An overall classification accuracy of 83% was obtained. A detailed description of developing land cover classes from the 2008 Landsat TM image is provided in Li et al. (2011).

For this work, each of the initial land cover classes was aggregated and recoded into the following groups: forest and SS3 were combined into a class identified as 'forest'; SS1 and SS2 were combined into a class identified as 'secondary succession (SS)'; pasture and burned areas were combined into a class identified as 'agriculture'; impervious surfaces were renamed 'urban'; and wetlands and water were combined into a class identified as 'other land cover'. Further, the amount of different soil types within all watersheds (including the 25 study watersheds) was calculated from the watershed data set described above and a spatial data set of soil type and location (Bliss, 2005).

2.3. Sampling water chemistry in streams

Each stream sampling location was visited approximately every three weeks from August 2008 until November 2008 in the dry season (which generally lasts from July to November) and December 2008 until April 2009 in the rainy season (which generally lasts from December to June). A total (n) of 250 samples were collected in 10 sampling time periods: five sample periods per season (dry and wet seasons) at each of the 25 streams. At the time of sample collection, DO, temperature, electrical conductivity (EC), and stream discharge (Q) were measured in situ using a DO and temperature meter (Extech Digital Dissolved Oxygen/Temperature Meter, Extech, Waltham, MA), a conductivity and temperature meter (HM Digital EC/TDS/Temp Combo Meter, HM Digital, Inc., Culver City, CA), and estimated assessments of stream width (with a meter stick), depth (with a tape measure), and water velocity (recording the time a partially or fully submerged leaf traveled a given distance in the main channel flow of water – a length of more than several meters that was unaffected by wind or other obstacles or barriers) (Gordon, McMahon, Finlayson, Gippel, & Nathan, 2004; Gore, 2006). Further description can be found in Cak (2011).

For each sample collection, duplicate water samples were collected from the main channel flow of water, approximately 5–10 cm below the water surface, using 60 mL syringes (BD Syringes, BD, Franklin Lake, NJ). Samples were filtered through 0.7 μm filters (Whatman GF/F glass microfiber filters, Whatman, Maidstons, UK) and placed into 30 mL HDPE plastic bottles (Nalgene, Nalge Nunc International Corporation, Rochester, NY). Bottles were pre-rinsed with filtered stream water, filled to capacity, and frozen within a few hours of collection. All water samples were analyzed at a laboratory of the Brazilian Agricultural Research Corporation (EMBRAPA) in the city of Belém, Brazil, immediately at the end of all fieldwork. Samples were analyzed for dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and total dissolved nitrogen (TDN) by combustion (Shimadzu TOC V, CSN, Columbia, MD); and Ca^{2+}, Cl^{-}, Mg^{2+}, nitrogen as ammonium (NH_4^{+}-N), nitrogen as nitrate (NO_3^{-}-N), PO_4^{3-},K^{+}, Na^{+}, and sulfate (SO_4^{2-}) by ion chromatography (Dionex DX-120, Sunnyvale, CA) (APHA, 1998).

Standard solutions (Shimadzu, Columbia, MD and Dionex, Sunnyvale, CA) were used to generate standard curves with correlation coefficients greater than 99.9% for all measured variables, except for NH_4^+-N, which had a correlation coefficient of 98.0%. During analyses, standards of varying concentrations were placed in-between every 10–20 samples for quality assurance. However, some ionic components exhibited a moderately high coefficient of variation (~20–30%) at smaller concentrations (Cak, 2011); as a result, samples that were found to be below an estimated limit of detection (LOD) determined from the lowest standard concentration of each ionic component were replaced by one-half the LOD value in all analyses (Helsel, 2005). While this approach may have underestimated the analytical results, the concentrations of each component were still well within the range of data found in comparable studies in nearby areas (Figueiredo et al., 2010; Tomasella, Neill, Figueiredo, & Nobre, 2009).

2.4. Interviewing households about land use, demographics, and water use

For each studied watershed, a random spatial sample of associated households was selected for interviews that discussed household demographic information (i.e., a household's arrival to the region and the property, and number of residents on the property), agricultural production and decision-making methods (i.e., use of fertilizers, herbicides, and fire for clearing land), and several aspects related to stream and water use (i.e., sources of drinking and agricultural water, and identification of changes in stream water quality, stream water flow/quantity, amount of fish in streams, and rainfall). The boundaries of these properties (previously identified with an overall spatial accuracy of 95% by researchers at the Anthropological Center for Training and Research on Global Environmental Change at Indiana University) in most instances encompassed the entire area of the watershed, though a few watersheds were significantly larger, making it unfeasible to interview all available households. Additionally, for the three urban watersheds, only urban households were interviewed (e.g., nonrural households in close proximity or next to the stream); this choice was made to best identify the household characteristics that would potentially impact the water chemistry responses found in these streams. For rural interviews, these direct impacts were addressed by interviewing households whose properties encompassed most or all of a studied watershed. Approximately 1–4 interviews were associated with each watershed and approximately 10 respondents were interviewed for two of the urban watersheds (Altamira and Medicilândia) to remain relatively consistent with the number of interviews for other watersheds, though we acknowledge that these numbers do not fully reflect the total populations for these cities (n = 74). Responses to interview questions were coded as binary yes/no answers and summed or averaged for each watershed in statistical analyses.

2.5. Statistical analyses

To characterize interviewed households in the study, a hierarchical cluster analysis of the household survey data was performed using the fpc package in R after calculating a dissimilarity matrix of the data (Hennig, 2014). Three clusters were identified that best categorized these data, as suggested by the pamk test (or partitioning around medoids with estimation of number of clusters). Basic statistics were summarized according to these clusters in order to categorize different types of households in the study.

To characterize the watersheds surveyed in the study, an additional hierarchical cluster analysis was performed on the stream water chemistry data and the percent and type of land cover, soils, and households (determined from the test described above) in each watershed, after calculating a dissimilarity matrix of the data. Square root transformations were used on the land cover, soil, and household data and log transformations were used on the stream water chemistry data to meet statistical assumptions for all tests. Three clusters were determined to best categorize these data, though the pamk test suggested 10 clusters (that were difficult to interpret easily). Basic statistics for all data were summarized according to these watershed cluster types. Single-factor and two-factor analysis of variances (ANOVAs) using R were performed on all variables according to their watershed cluster assignments (R Core Team, 2014).

To examine the relationships among the collected or measured watershed data (stream water chemistry and percent and type of land cover, soils, and households) without a priori clustering, a partial least-squares canonical analysis (PLS-CA) was performed using the package plsdepot in R (Sanchez, 2012). While based on partial least-squares regression, PLS-CA describes the relationship between two data matrices that are 'simply two sets of descriptors' (Sanchez, 2014). PLS-CA summarizes the relationships within and between data matrices to create a new set of components that explain these relationships together. The result of this analysis is a correlation plot of components that describes the strength of correlations with these components. As discussed by the author of this R package (Sanchez, 2014),

> This plot can be regarded as a radar. The closer a variable appears on the perimeter of circle, the better it is represented. In addition, if two variables are highly correlated, they will appear near each other. If two variables are negatively correlated, they will tend to appear in opposite extremes. If two variables are uncorrelated, they will be orthogonal to each other.

In this analysis, one matrix was comprised of stream water chemistry data, while the other matrix was comprised of variables that could affect stream water chemistry: the percent and type of land cover, soils, and households in watersheds.

3. Results

3.1. Classification of households by land use, demographics, and water use

As described above, hierarchical cluster analysis identified three distinct types of households in the study area, with each cluster generally corresponding to a household's arrival date to the property or region and a household's primary form of agricultural production. In one cluster of households (n = 36) described as 'older/cocoa', household residents typically arrived to their properties or the study area in the early 1980s (Table 1). Properties with these households also had the largest number of residents among the three different types of households. While cocoa production was their dominant activity, 'older/cocoa' households reported a broad range of agricultural activities, including cattle ranching and other perennial and annual agriculture. Corresponding to these more intensive agricultural activities, this group also reported greater use of fertilizers, herbicides, and use of fire to clear areas of land compared to the other household clusters.

In a second cluster of households (n = 21) defined as 'middle age/cattle', household residents typically arrived to their properties or the study area in the early 1990s (Table 1). Compared to the 'older/cocoa' household type, 'middle age/cattle' households reported fewer residents living on the surveyed properties. While cattle ranching was their dominant agricultural activity, these households were engaged in a range of agricultural activities, including cocoa, perennial, and annual agriculture, though to a lesser degree

Table 1. Household demographics, income, and land and water use responses by three different types of households identified from hierarchical cluster analysis: (1) an older household generally involved in cocoa agriculture, (2) a middle-aged household generally involved in cattle ranching, and (3) a younger household generally living in urban areas and not directly involved in agriculture.

	Household type			Total
Demographic, income, and land and water use responses by households	Older/ Cacao	Middle age/ Cattle	Younger/ Urban	
Number of interviewed households	**36**	**21**	**17**	**74**
A *Household information*				
From Brazilian north	11.1%	9.5%	35.3%	16.2%
Average (±SE) year arrived to lot	1981 ± 3	1991 ± 3	2001 ± 2	1989 ± 2
Average (±SE) number of property residents	13.8 ± 4	5.4 ± 1	5.0 ± 1	9.4 ± 2
Primary income source				
Agriculture	100.0%	100.0%	58.8%	90.5%
Business	0.0%	9.5%	41.2%	12.2%
Others (e.g., pension, other types of work)	0.0%	0.0%	29.4%	6.8%
B *Stream and water use*				
Household water sources				
Well	86.1%	81.0%	76.5%	82.4%
Government	0.0%	0.0%	47.1%	10.8%
Stream	16.7%	4.8%	0.0%	9.5%
Others (e.g., spring, cistern, dam)	22.2%	14.3%	0.0%	14.9%
Sewage/waste disposal				
'On property'	36.1%	42.9%	11.8%	32.4%
Cesspit	58.3%	28.6%	17.6%	40.5%
Stream	0.0%	4.8%	70.6%	17.6%
Average reported stream uses[a]	2.2 ± 0.2	1.4 ± 0.2	0.5 ± 0.2	1.6 ± 0.1
Eat fish from streams	66.7%	66.7%	17.6%	55.4%
Maintain riparian buffer along stream	94.4%	95.2%	0.0%	73.0%
Maintain dam along stream	22.2%	47.6%	0.0%	24.3%
C *Agricultural use*				
Cleared area of forest in the last five years	41.7%	19.0%	0.0%	25.7%
Used fire to clear an area of land	27.8%	19.0%	0.0%	18.9%
Apply fertilizers	61.1%	9.5%	0.0%	32.4%
Use herbicides, insecticides, etc.	75.0%	9.5%	0.0%	39.2%
Produce cacao	77.8%	52.4%	0.0%	52.7%
Cattle ranching	66.7%	85.7%	0.0%	56.8%
Other perennial agriculture	27.8%	4.8%	0.0%	14.9%
Annual agriculture	33.3%	28.6%	0.0%	24.3%
D *Environmental awareness*				
Average reported changes[b]	2.5 ± 0.2	2.3 ± 0.2	2.1 ± 0.2	2.4 ± 0.1

Notes: [a]Respondents could report up to four stream uses: (1) laundry, (2) bathing, (3) recreation, and/or (4) other uses (e.g., gardening/some agriculture, reporting others' general use (but not their own)).[b]Respondents could report up to four environmental changes for the following categories: (1) changes to fish stocks over time (increase/decrease), (2) changes in the quantity of rain over time (increase/decrease), (3) changes in the flow/amount of water in streams over time (increase/decrease), and/or (4) changes in the water quality of streams over time (dirtier/cleaner).

than the 'older/cocoa' households. Use of fertilizers, herbicides, and fire to clear areas of land was not as frequent in this cluster.

In the third cluster of households (n = 17) designated as 'younger/urban', household residents typically arrived to their properties or the study area in the early 2000s (Table 1) and had the largest percentage of residents from the Brazilian North (e.g., the Amazon region, likely the children of earlier colonists). While households in this cluster reported some involvement from agriculture (e.g., for income), these households earned income mainly from nonagricultural activities, such as owning or managing a business, working in a nonagricultural job, or receiving a pension.

Across all three types of households, most residents obtained water for domestic use from wells, with urban residents also receiving municipal water when available. A small percentage of residents in the rural areas (17% of the ‘older/cocoa’ households and 5% of the ‘middle age/cattle’ households) reported obtaining water for domestic use from streams and rivers on their properties. Additional sources for household water included from springs, cisterns, and dams. While rural residents generally disposed of household waste in cesspits or somewhere on their properties, the interviewed urban residents disposed of household waste directly into streams. Rural residents also used streams more frequently than urban residents, including bathing, recreation, and as a source for food (fish). In addition, rural residents reported maintaining a riparian buffer along streams, while some rural residents, particularly from ‘middle age/pasture’ households, maintained dams on streams running through their properties. In response to questions about changes to water resources over time (e.g., ‘Has there been more or less rain compared to the past?’; ‘Is stream water flow higher or lower compared to previous years?’; ‘Is stream water dirtier or cleaner compared to previous years?’; and ‘Has there been a change in the amount/number of fish in streams compared to previous years?’), the three household types did not exhibit any discernable differences.

3.2. Classification of watersheds by land use, soil type, water chemistry, and households

Similar to the classification of households, hierarchical cluster analysis identified three distinct types of watersheds in the study area, with each cluster generally corresponding to certain types of households and associated land cover (Figure 2). One cluster of watersheds (n = 12) was represented by cocoa agriculture, with most households in these watersheds classified as the ‘older/cocoa’ type and forest as the dominant land cover, followed by lesser amounts of agriculture/pasture and secondary forest regrowth (SS). A second cluster of watersheds (n = 10) was related to cattle ranching, with most households in these watersheds classified as the ‘middle age/cattle’ type, though some ‘older/cocoa’ households also were present. Similar to the cocoa agriculture-based watersheds described above, forest was the dominant land cover, though these watersheds had relatively higher percentages of agricultural land cover (e.g., pasture). A third cluster of watersheds (n = 3) corresponded to the three urban watersheds, with all interviewed households in these watersheds characterized as the ‘younger/urban’ type. Despite being classified as urban watersheds, agriculture was the dominant land cover type, though urban land cover and some SS and forest also were present.

Across the three different types of watersheds, soils generally were identified as yellow latosols (oxisols) or deep, well-drained acid clays according to the Brazilian system of soil classification (EMBRAPA, 1999). However, considerable variability among soil types was found within and across the different types of watersheds (Figure 2). For example, soil in one urban watershed was comprised of a high percentage of fertile *terra roxa* soil. Similarly, watershed and stream size varied among and within the different types of sampled watersheds; the smallest studied watershed was 1.66 km^2, while the largest was 194 km^2, and the overall median size was 9.66 k m^2 (Figure 3). The

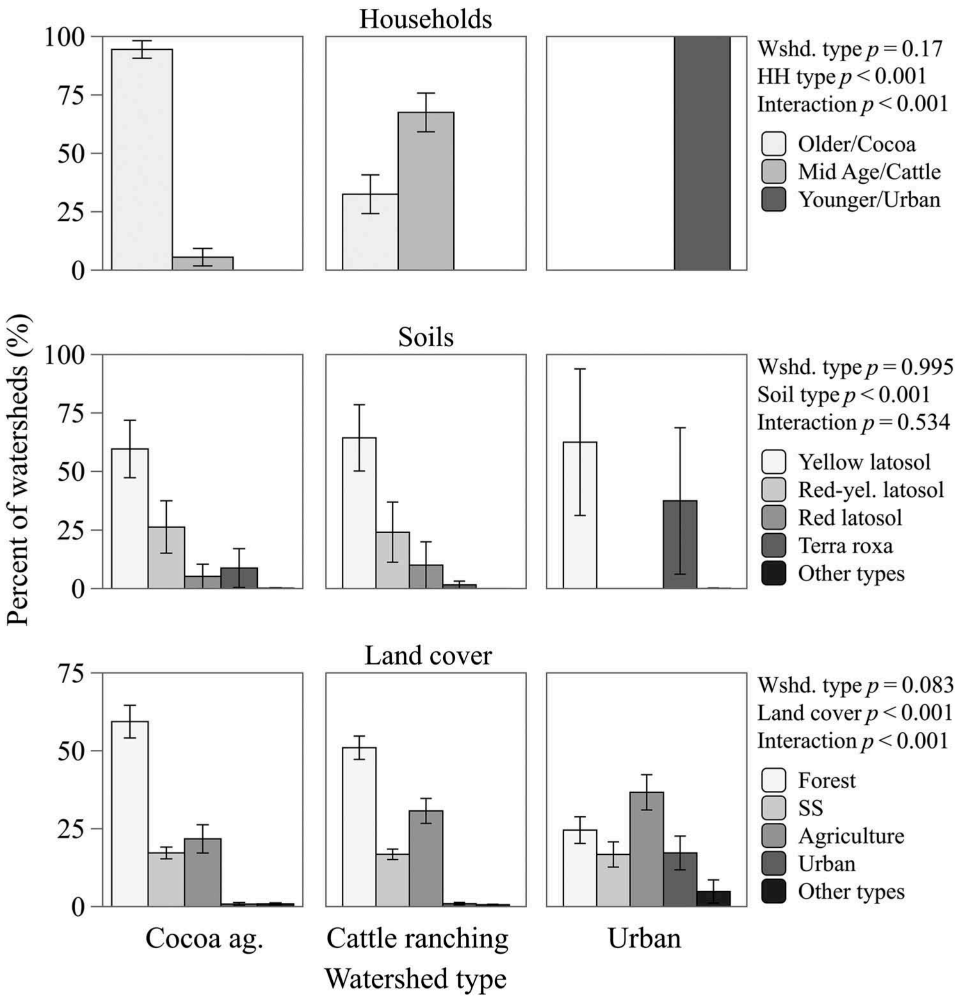

Figure 2. The percent of different types of households, soils, and land cover in three types of watersheds identified in the study: (1) watersheds identified predominantly by cocoa agriculture, (2) watersheds identified predominantly by cattle ranching, and (3) watersheds identified predominantly by urban development. Responses from two-factor ANOVAs also are shown.

median discharge for all streams was 0.23 $m^3 s^{-1}$. Predictably, discharge was greater in the wet season than in the dry season across all studied streams, though variability in discharge was much larger in the wet season. For both watershed area and discharge, no significant differences were found between the different types of watersheds (cocoa agriculture-based, cattle ranching-based, or urban). Differences in discharge from dry and wet seasons, however, appeared to be larger in watersheds with cattle ranching compared to the other watershed types, though this result was not significant.

For most stream water chemistry variables, streams draining urban watersheds generally had higher concentrations relative to streams from the other two types of rural watersheds (Figure 4), including several major ions (Ca^{2+}, Cl^-, and SO_4^{2-}). Concentrations of other ions and DIC, which was dominated mainly by HCO_3^- in these aquatic systems, also had larger

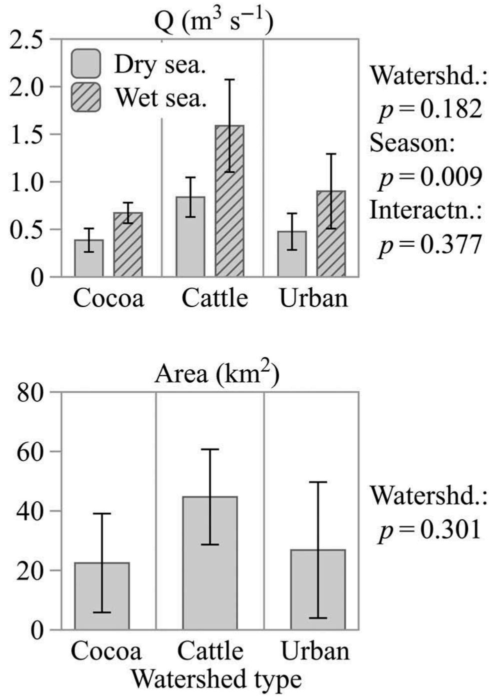

Figure 3. Watershed size and stream discharge measured in three different types of watersheds identified in the study: (1) watersheds identified predominantly by cocoa agriculture, (2) watersheds identified predominantly by cattle ranching, and (3) watersheds identified predominantly by urban development. Responses from one- and two-factor ANOVAs also are shown.

but not significant increases in urban watersheds relative to rural watersheds (Mg^{2+}, Na^{+}, and K^{+}). Further, urban streams had higher concentrations of all measured forms of nitrogen (NO_3^{-}, NH_4^{+}, and TDN) and PO_4^{3-} (which generally was at or below the LOD for most streams), along with higher water temperatures. Not surprisingly, the urban streams had lower concentrations of DO relative to the other two types of rural streams. For streams draining rural watersheds, few significant differences in stream water chemistry variables were found, with streams draining cocoa agriculture-based watersheds occasionally containing slightly higher concentrations of some ions (though generally not significant) relative to streams draining cattle ranching-based watersheds.

Discharge was a moderating factor for several of the stream water chemistry variables measured. Predictably, several stream water chemistry metrics, including concentrations of K^{+}, SO_4^{2-}, and DOC were larger in the wet season than the dry season. However, concentrations of several other stream water chemistry metrics decreased from the dry season to the wet season, including Cl^{-}, DIC, Na^{+}, as well as the measured EC. Ca^{2+} decreased from the dry season to the wet season for streams draining rural areas, but slightly increased from the dry season to the wet season in urban streams. In contrast, NH_4^{+} followed the opposite trend for rural and urban streams (though this result was not significant). PO_4^{3-} appeared to increase during the wet season, but the response was highly variable within and among watershed types, likely due to the very low concentrations that generally were near the LOD of analyses. Temperature and DO did not appear to be affected by seasonal differences in discharge.

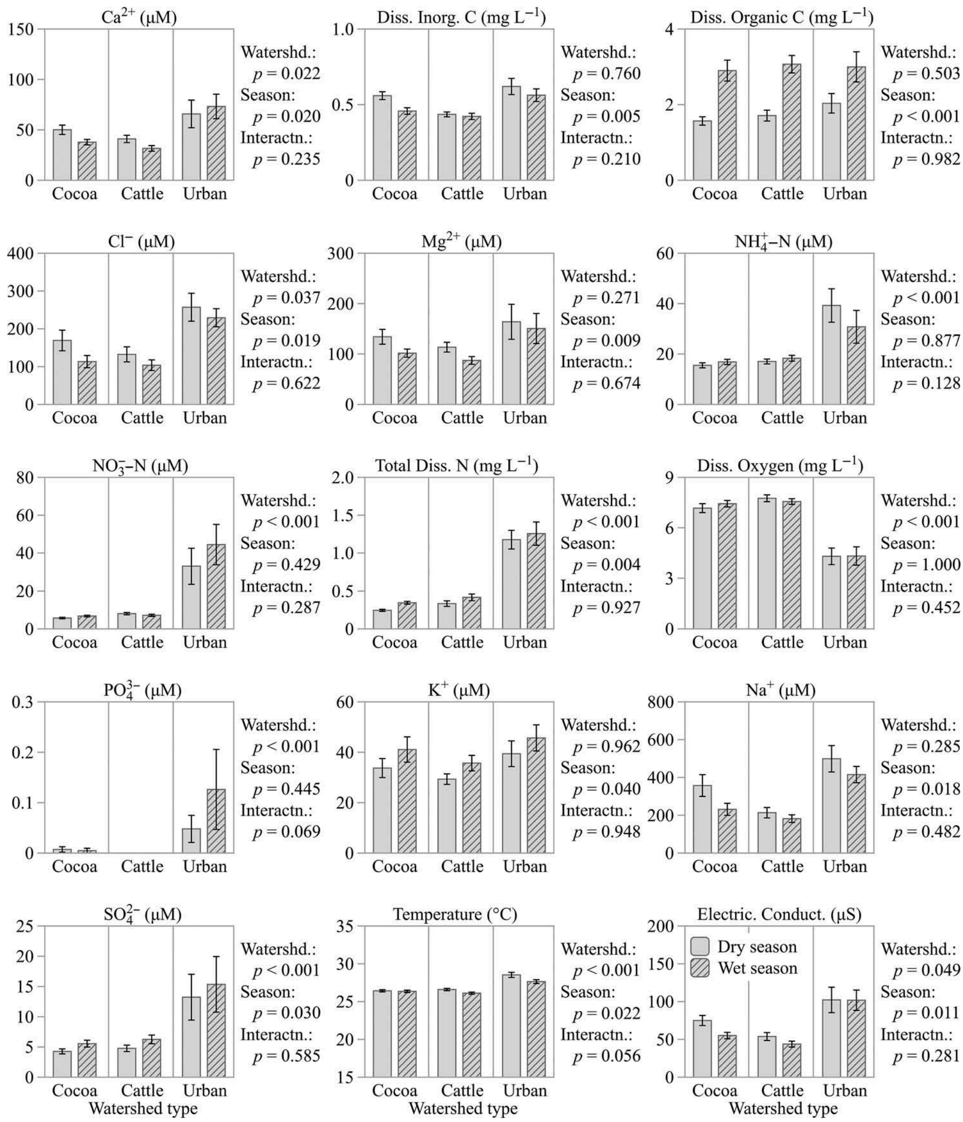

Figure 4. Water chemistry responses measured in three different types of watersheds identified in the study: (1) watersheds identified predominantly by cocoa agriculture, (2) watersheds identified predominantly by cattle ranching, and (3) watersheds identified predominantly by urban development. Responses from two-factor ANOVAs also are shown.

3.3. Relationships between land cover, soil type, water chemistry, and households

The PLS-CA, used to assess the relationships between all measured variables without a priori classification, highlighted similar patterns as the analyses described above (Figure 5). For example, watershed area and stream flow (Q) did not exhibit strong relationships with other variables in the test, as evidenced by their short correlation lines and orthogonal direction from most other variables. In contrast, many other watershed variables (e.g., the percent of different types of households, many types of

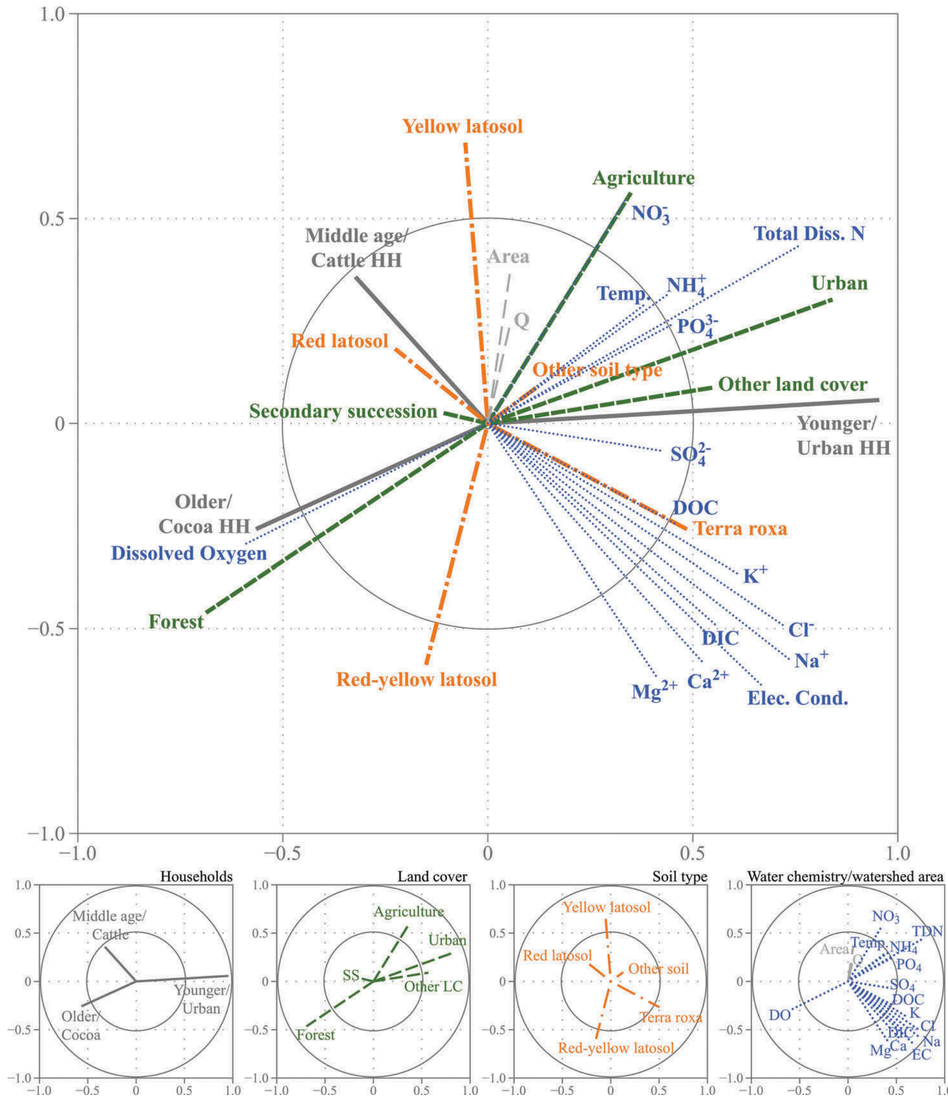

Figure 5. Results of partial least squares canonical analysis (PLS-CA) of the percent of different types of households, soils, and land cover together with stream water chemistry variables. The length of lines indicates the strength of correlations of each variable in the test, while the direction and location of each line represents the correlation of one variable with another (e.g., lines adjacent to each other in the same direction are more positively correlated, lines orthogonal to each other are weakly correlated, and lines in opposite directions are negatively correlated). Shown in the smaller figures (to aid visualization and interpretation) are the separate responses for household types, land cover types, soil types, and stream water chemistry metrics.

land cover, a few types of soil, and many stream water chemistry metrics) were well represented in the test, as indicated by the length of each variable's correlation line (which was frequently greater than 0.5, or a strong correlation in the test).

The pattern of relationships among and between correlation lines for households and land cover suggested that watersheds generally did not have a mixture of different types of households, as the orientation of their correlation lines was in different or opposite directions (e.g., negatively correlated). Given the close distance and parallel direction of their correlation lines, the amount of forest in watersheds was positively correlated with the number of 'older/cocoa' households in watersheds (e.g., more forest corresponded with more of these households), while the amount of urban land cover was positively correlated with the number of 'younger/urban' households. The amount of 'other land cover' (water, wetlands) also was positively correlated with this household type, likely due to the abundance of wetlands and water in one urban watershed (draining the city of Altamira). The amount of agriculture (e.g., pasture) in watersheds was somewhat positively correlated with the number of 'middle age/cattle' and 'younger/urban' households in watersheds, as the correlation line for this variable fell in between the correlation lines for these household types. SS did not appear to be strongly correlated with variables in this test, likely due to its variability among watersheds. Overall, forest, urban, and agricultural land cover variables were well represented in the test (e.g., long correlation lines), while SS and, to a lesser degree, 'other land cover' (e.g., water, wetlands) were not as well represented.

Further, the orientation of correlation lines for the percent of different soil types in watersheds was in different or opposite directions, indicating that watersheds generally did not have a mixture of soil types. The percent and types of soil were only somewhat correlated with the household and land cover variables, falling in between or orthogonally to the correlation lines for most, though the percent of red latosols in watersheds was positively correlated, albeit weakly represented in the test, with the amount of 'middle age/cattle' households.

For stream water chemistry variables, the concentration of DO was positively correlated with the amount of forest and the number of 'older/cocoa' households in watersheds (e.g., watersheds where streams had higher DO concentrations also appeared to contain more forest and more of these types of households, as suggested by the close distance between correlation lines). Concentrations of several major ions (Mg^{2+}, Ca^{2+}, Na^{+}, Cl^{-}, and K^{+}) and the two measured forms of carbon (DIC and DOC) were positively correlated with the amount of *terra roxa* in watersheds, and to a lesser degree with the amount of red-yellow latosols; these water chemistry metrics also were somewhat positively correlated with the amount of urban land cover and associated households. Further, concentrations of all measured forms of nitrogen (NO_3^{-} and NH_4^{+}, as well as TDN) and PO_4^{3-}, together with stream water temperature, were positively correlated with the amount of agricultural land cover, urban land cover, and associated urban households.

4. Discussion

4.1. Watershed land cover changes and outcomes for streams

In the Amazon, research about land use and household demographics, especially in the Altamira region, has identified strong links between household characteristics such as age, size, and the amount and type of land clearing (VanWey, D'Antona, & Brondizio, 2007; Walker, Perz, Caldas, & Silva, 2002). In this work, three demographic profiles of property owners were identified: those who arrived to their properties in the early 1980s, those who arrived to their properties in the early 1990s, and those who arrived to their properties in the early 2000s. These demographic patterns may indicate either the arrival of new waves of young colonists to the area, or more likely, the movement of children or relatives of early settlers to begin agriculture on new properties or to live in cities. Households at each of these stages in their life cycles appeared to be engaged primarily in one general form of agriculture or lifestyle: older households with cocoa agriculture, relatively younger households with cattle ranching, and the youngest households living in urban areas.

These choices corresponded to identifiable landscape patterns within and among watersheds. Watersheds with a dominant number of older households engaged in cocoa agriculture generally contained more areas of abundant forest, secondary succession forest regrowth, and agroforestry. In contrast, watersheds with a dominant number of slightly younger (middle age) households engaged in cattle ranching contained more areas of other agricultural clearing and use (e.g., pasture), while watersheds with the youngest group contained areas of urban development. These results confirm the hypotheses of this study, as well as complement the findings of other studies that implicated younger households with more deforestation and clearing than older households (McSweeney, 2004; Walker et al., 2009), though those studies did not consider urban households. Younger households may be motivated to clear land at a greater rate and scale than older households for many reasons, including the desire for increased income early in the household life cycle – for which cattle ranching provides less upfront investment costs relative to cocoa agriculture (Brondizio et al., 2002; Sherbinin et al., 2008).

Household activities within watersheds had both direct (e.g., use of stream resources) and indirect (e.g., landscape impacts resulting from decisions about land use and land cover) effects on several water chemistry metrics of small streams. Changes in the amount of forest cover, such as forest being replaced by pasture, urban development, perennial or annual agriculture, or some other type of land cover, had clear effects on concentrations of nitrogen, phosphorus, and DO, as well as water temperature. Such changes have been seen elsewhere in the Amazon (Deegan et al., 2010; Figueiredo et al., 2010; Macedo et al., 2013; Tomasella et al., 2009), though this is one of the first studies to directly extend an analysis of household demographic patterns to include their impacts to stream water chemistry. While this study found higher concentrations of nitrate to be linked with deforestation, pasture, and urban development, previous studies have noted variable responses, including decreases and increases with agriculture (Figueiredo et al., 2010) and urban development (Primo dos Santos, 1997).

Importantly, water resources, particularly streams and rivers, were both protected and widely used by respondents. Most rural respondents used streams and rivers for agricultural production and some household domestic needs, such as bathing, laundry, food, and drinking water, though they did not express strong opinions or views about the quality of water that was used. Of the few previously identified studies describing water use by Amazonian households, these also have noted similar uses by residents and colonists (McClain & Cossío, 2003; Moran, 1993). However, one of the strongest findings of this study was the potential influence of household waste disposal on stream water chemistry (i.e., the strong correlations between urban households where waste was disposed directly into streams and the responses of stream water chemistry metrics, especially increased nitrogen and phosphorus). Trash and waste in streams and rivers is a growing problem in the Amazon, particularly in urban areas such as the capitals of Manaus and Belém (Aragon & Clüsener-Godt, 2003; Parry, Peres, Day, & Amaral, 2010), but this study firmly documents that similar instances also are occurring in streams of smaller cities and rural areas.

Some water chemistry metrics, including DOC, did not show strong responses to household activities or land use. Other metrics appeared to be more closely associated with soil types, though this result was not consistent across statistical tests. For example, *terra roxa*, which generally has higher nutrient concentrations and has been prized by local residents for facilitating productive agriculture (Moran, 1993; Moran et al., 2002), was associated with several water chemistry components, such as calcium, DIC, magnesium, sodium, and chloride in one statistical test, while these components also appeared to be associated (both statistically significant and not) with urban land use in another test. One study noted that deforestation often occurred in areas with high cation contents in soils, thereby confounding the effect of deforestation on cation concentrations in stream water (Biggs, Dunne, Domingues, & Martinelli, 2002). However, it is possible that many of these high ionic concentrations in stream water that were associated with soils were the result of chemical weathering, which may have been precipitated by land cover changes leading to increased soil erosion and runoff in streams (Neill et al., 2011; Tomasella et al., 2009). The direct measurement of soil type and location was not assessed in this study, however.

Similarly, discharge also affected several of the measured water chemistry metrics in variable ways, with some metrics increasing from the dry season to the wet season and others decreasing. Seasonal differences in discharge appeared to be one of the primary influencing factors for responses by DOC and potassium. Interactions between season and watershed type, while not statistically significant, also were seen, with responses of ammonium and calcium varying across rural and urban watershed types by season (e.g., increasing in rural watersheds from dry to wet seasons and decreasing in urban watersheds and vice versa, respectively). This result highlights the unique impact of urban development for these metrics. Further, seasonal differences in stream water chemistry in cocoa-growing watersheds appeared to be more tempered (e.g., less of an increase from the dry season to the wet season and considerably less variable in the wet season) relative to cattle ranching and urban watersheds.

Overall, while watersheds experiencing agriculture and urban development showed relatively similar patterns in stream water chemistry (e.g., elevated concentrations of some metrics in some tests), streams draining urban areas consistently exhibited larger effects relative to all other streams (e.g., the lowest DO concentrations, the highest concentrations of calcium, nitrogen, phosphorus, sulfate, sodium, and chloride, and the highest water temperatures, etc.). Significantly, the urban watersheds we studied also contained forested and agricultural areas, thus highlighting the role that urban development played in the composition of stream water chemistry; the urban 'signal' appeared to trump any effects by other types of land use and land cover in a catchment. Following fieldwork, the study area and the city of Altamira in particular experienced a dramatic surge in population related to the construction of the Belo Monte hydroelectric dam (Leite, Amora, Kachani, De Almeida, & Machado, 2013); as to be expected, this population increase has corresponded with significant development around Altamira, and we anticipate these results to (1) serve as a basis or 'before' point in describing the conditions of stream water prior to this population surge as well as (2) serve as a model of future impacts for the surrounding area.

4.2. Conclusion

Throughout the Amazon, land use changes, especially clearing for pasture and urban development, have dramatically altered the structure and function of watersheds and associated streams. This study identified several different types of residential households in the Amazon, each with unique signatures on the composition of the surrounding land cover and the corresponding stream water chemistry. Older households generally were associated with areas of abundant forest, agroforestry activities such as cocoa production, and 'improved' stream water quality, such as higher DO concentrations and lower stream water temperatures. Importantly, these 'higher quality' stream responses were found despite these areas also being associated with agricultural chemical and fertilizer use. In contrast, one slightly younger (middle age) group of households was related to areas of other agricultural clearing and use (e.g., pasture for cattle ranching), while the youngest group was associated with areas of urban development. Both the 'middle age' and youngest households (and their land use patterns) corresponded with streams containing higher concentrations of many ions (especially nitrogen and phosphorus), increased stream water temperature, and decreased DO concentrations.

Many efforts to understand and mitigate the impacts of deforestation have been focused on activities that can be widely applied to different regions; however, as shown by this study, localized impacts from land use and urban development can be significant, especially for streams and rivers. As a result, a uniform policy of environmental enforcement in the Amazon may not be successful, given the diverse and distinct range of environmental and economic needs across the Amazon. Improved focus on the importance of healthy and clean aquatic ecosystems is necessary, especially increased public awareness about the negative effects of trash and waste disposal on stream and river water quality coupled with a more active government role to undertake mitigation and cleanup efforts when needed. One respondent in this study mentioned during an interview that we were the first group to have ever visited his property asking about streams and water, including Brazilian agricultural extension agents, which was a great surprise given the widespread prevalence and importance of water in the Amazon Basin. This interaction highlighted the fact that stream water often has been ignored in Amazonian policy.

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