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How management alternatives of fast-growing forests affect water availability in southeastern Brazil: insights from a paired catchment experiment

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October 5, 2020

Abstract

Fast-growing plantations have been expanding in Brazil in the last 50 years, increasing productivity by over 40 m3 / ha in reduced cycles between 5 and 15 years. In the 1990s, environmental warnings about these plantations guided research projects seeking to understand their effects on water and propose forest management actions to minimize them. The assessment of forest management effects on water resources is conducted by long-term experiments in paired catchments. In this study, we present some studies conducted at the hydrological monitoring center of Itatinga Experimental Station, of the University of São Paulo, where hydrological monitoring began in 1987, and currently conduct 4 catchments under different forest management regimes: fast-growing industrial management, long-term forest mosaic management, native forest restoration and long-term coppiced management. Results show that in a site with deep soils and good natural water regulation, main hydrological effects still occur when forest management intensifies, increasing water consumption and making the flow regime vulnerable to intra- and inter-annual seasonality. Regarding water quality, weekly sampling showed little interference of forest management on water chemistry; besides, more intensive management increased the concentration of nutrients in the water. There were no differences in water use in Eucalyptus plantations aged between 10 and 17 years and the use of coppice management had in the first 2 years higher water use than new plantations. The different types of management adopted directly affected the amount of water used, showing that high water demand forest plantations at water deficit regions, water availability is directly controlled by the forest management regime.

1. Introduction

Fast-growing forest plantations represent an important part of the economy of countries located in the tropical region (Payn et al., 2015), expanding in the last decade mainly to meet the demand for cellulose for industry (Costa & Oliveira, 2019). The expansion of forest plantations to regions with greater human presence and occupying areas previously used by agriculture is responsible for the existence of some conflicts, among which those related to water use stand out (Cao & Zhang, 2015; Ferraz, Rodrigues, Garcia, Alvares, & Lima, 2019; Gerber, Veuthey, & Martínez-Alier, 2009; Van Wilgen & Richardson, 2012).

The concern about water use by fast-growing plantations is old in these regions and mainly results from the early period of the introduction of plantations, when environmental regulation was lower, forest management

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technology was developing, and the socio-environmental commitments of the companies were not yet so clear (Lima, Ferraz, Rodrigues, Zakia, & Salemi, 2017).

As a result of this period, the debate on the hydrological effects of plantations lasted for years and still persists (Scott, 2005), although several studies on forest hydrology have begun (Sahin & Hall, 1996; Scott, 2005) and already have results that can clarify the initial doubts (Farley, Jobbagy, & Jackson, 2005; Van Dijk & Keenan, 2007) and guide forest management and public policies (Ferraz et al., 2013; Little et al., 2014). Among the studies conducted, we highlight the hydrological monitoring of catchments in production areas which evaluates the effects of forest management on the quantity and quality of water (Ferraz et al., 2019; Neary, 2016; Scott & Prinsloo, 2008).

Brazil occupies a prominent position in this debate, not only because of the high productivity of plantations (Stape et al., 2010) and expansion of the sector (FAO, 2020), but also because of the location of plantations in regions with lower water availability, where some conflicts for water use begin to emerge (Ferraz et al., 2019). And following the development of the sector, research in forest hydrology in planted forests began in the late 1980s with hydrological monitoring in catchments (Arcova & Lima, 1985; Lima, 1988; Lima, 1987). Among them, the experimental area of the University of São Paulo located in Itatinga-SP stands out with one of the first experimental catchments to evaluate the effects of forest management in Brazil (Lima, Ferraz, Rodriguez, & Voigtlaender, 2012).

Currently, the debate on the hydrological effects of plantations has been changing from water use by forest plantations (Calder, Hall, & Adlard, 1992), or their comparison with native forests (Hou, Duan, Tang, & Fu, 2010; Klinge, Schmidt, & Fölster, 2001; Salemi et al., 2013), to which changes in forest management can reduce effects on water use and regulation in production areas (Dai, Wang, Zhu, & Xi, 2017; Vanclay, 2009). Despite the potential for reduction of effects from changes in the landscape scale, such as reduction in the occupation of the catchments by the plantations (Lima et al., 2012; Little, Cuevas, Lara, Pino, & Schoenholtz, 2014), or use of the mosaic of ages (Ferraz, Lima, & Rodrigues, 2013) and even advance in soil and water conservation techniques by forest management (Aust & Blinn, 2004; Silva, Silva, Curi, Avanzi, & Leite, 2011), there are still gaps in knowledge about forest management strategies related to the rotation cycle (Scott & Prinsloo, 2008; Vertessy, Watson, & O'Sullivan, 2001), conduction of regrowth (Neary, 2016), strategies for locating plantations in the landscape (Kalantari et al., 2014), in addition to the climatic influence of past years (David, Henriques, David, Tomé, & Ledger, 1994).

As these situations are not commonly used in commercial management of plantations, the monitoring of different forest management strategies is more difficult to implement and is restricted to experimental areas (Tetzlaff, Malcolm, & Soulsby, 2007). In this study we analyzed the hydrological regime of 3 paired catchments under different types of forest management including cutting, regrowth, ages and forest types, which allows us to understand the effects of forest management on the quantity and quality of water.

2. Material and Methods

Study area

The Forest Sciences Experimental Station of Itatinga (*Estação Experimental de Ciências Florestais de Itatinga* - EECFI) is located in the municipality of Itatinga, São Paulo, Brazil, at an average altitude of 850 meters, occupying a total area of 2,118 hectares (Gonçalves et al., 2012). The climate in the region is classified as Cwa, humid temperate with dry winters and hot summers, according to Köppen's classification, with an average annual temperature of 19.4 °C and average annual precipitation of 1,319 mm (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013).

Soil type of catchments are Hapludox Typic and Rhodic, with texture varying from sandy loam to sandy clay loam, respectively (Gonçalves et al., 2012), with the same underlying geology (Sandstone from sedimentary rocks). The area is located in a transition region between the Cerrado and the Atlantic Forest, with fragments of semi-decidual seasonal forest and *Cerrado latu sensu* subjected to various levels of degradation (Sartori, Poggiani, & Engel, 2002).

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Paired catchments

The four catchments are on the same geological formation, sandstone from sedimentary rocks. The C1 catchment has 57.5% of its area under Rhodic Hapludox and 42.5% under Typic Hapludox, the same soil found in more than 95% of the area of the C2, C3 and C4 catchments. The catchments have similar physiographic characteristics (Table 1).

The catchments have riparian vegetation [native vegetation] preserved along the watercourses, with canopy of *Eucalyptus saligna* and understory with native species characteristic of semi-decidual seasonal forest in regeneration (Santos et al., 2019). The area with native vegetation represents 8%, 48%, 13% and 44% of the areas of the C1, C2, C3 and C4 catchments, respectively. The C1 catchment has a mosaic of forest plantations [forest mosaic] in 87% of its area, C2 has 52% of its area in the process of native forest restoration, and C3 and C4 have 80% and 50%, respectively, of their areas with commercial eucalyptus forests [Eucalyptus plantation].

The C1 catchment is under a regrowth cycle that underwent clearcutting in 1997 (Câmara & Lima, 1999). From harvest in 1997, the occupation of the catchment has been diversified with different species of*Eucalyptus spp.* , at different ages, in addition to planted forests of *Pinus spp.* , *Araucaria angustifolia* and*Acacia mangium* , in a smaller proportion, forming a forest mosaic of species and ages [forest mosaic].

The C2, C3 and C4 catchments were covered by clonal Eucalyptus plantations, under forest management in a short cycle (< 7 years) with conduction of regrowth. This management system was implemented more than 30 years ago in the area, with replanting of the plantations, on average, every 14 years. After the harvest in 2014, there was regrowth of the plantation without conduction, leading to a new clearcut in 2016 in the C2 and C3 catchments. In C2, after the clearcut of 2016, a native forest restoration process began in the area initially occupied by planted forests [eucalyptus plantation]; while in the C3 catchment there was the replanting of eucalyptus plantations. In the C4 catchment there was the conduction of the regrowth [eucalyptus coppice], initiated after the 2014 harvest.

C2 and C3 had their areas replanted in 2016. The forestry practices adopted in the implementation included the monitoring and control of leaf-cutting ants using granulated bait; control of invasive plants with chemical and manual weeding; application of dolomitic limestone in total area; subsoiling with agricultural tractor; manual planting of seedlings; basal and top-dressing fertilization with NPK; manual application of pre-emergent herbicide in the planting row and replanting of gaps.

Hydrological monitoring

Hydrological monitoring (quantitative and qualitative) began in 1991 in the C1 catchment, in 2013 in C2 and C3, and in 2018 in C4 (Figure 1). Flow monitoring in the four catchments is carried out using an H-type metal flume, with a maximum measuring capacity of 150 L s^{-1}. Flow rate is obtained from the equation proposed by Bos (1989). Water level height is obtained by Thalimedes water level meter with datalogger. From 2013, with the beginning of the monitoring of the C2 and C3 catchments, OTT Orpheus Mini pressure transducers were installed, same devices installed in C4 after its construction in 2018. Water level height data are obtained in an interval of 15 minutes.

Precipitation monitoring has been carried out at the EECFI meteorological station since 1991, initially by means of a PLG 75 rain gauge (Hidrologia S/A) and, currently, by means of a TR-5251 automatic rain gauge (Texas Electronics), with a record frequency of 30 minutes.

Water quality monitoring in the four catchments is carried out through weekly collections of 1 liter of water at the flume outlet, where the following parameters are analyzed in the laboratory: pH, electrical conductivity, suspended solids, turbidity, apparent color, nitrate, phosphorus, potassium, calcium and magnesium, following standardized procedures (APHA, 2005).

Hydrological analyses

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Flow data were integrated over time to obtain the daily and annual flow (Q), as well as the data of precipitation (P). Annual evapotranspiration (ET) was estimated based on the difference between annual P and Q (simplified equation of water balance). Water yield (Q:P) was calculated from the ratio of Q by P for the monthly and annual scales. The monthly water yield was compared by the Kruskal-Wallis test, and the differences were analyzed by the Mann-Whitney pairwise test.

Baseflow index (BFI) was calculated on the annual scale by the method of Lyne and Hollic (1979) described by Grayson (1996) using a digital filter. The flow duration curve (FDC) was constructed from the daily flow data (Gordon et al., 2004), from which the following percentiles were obtained: Q_{10}, representative of the maximum values, Q_{50} representative of median values and Q_{90} representative of the minimum values of flow for each catchment.

The data of total suspended solids (TSS) and nitrate (NO3) concentrations obtained in the C1, C2 and C3 catchments during the entire study period were analyzed using the Kruskal-Wallis and Mann-Whitney pairwise tests to detect differences between the data sets.

Table 2 shows the data periods for the 3 catchments, the indicators and the analysis scales used. For general characterization of the effects of forest management throughout the period in the 3 catchments, the daily variation of flow, baseflow and precipitation was analyzed. For water quality, medians of TSS and N were compared. The effect of age was assessed with data of the C1 catchment, from September 2009 to August 2019. The average age of the plantation in each water year was calculated by the average age of the plots weighted by the area of each plot. The comparison of the hydrological regime between restoration (C2) and commercial planting (C3) was performed for the period of two water years, from September 2017 to August 2019, and compared with the C1 catchment, considered as reference. The hydrological regime in the initial years of development of regrowth and post-replanting, for the period from May 2014 to April 2016 (regrowth) and from May 2017 to April 2019 (post-replanting), was analyzed from the data of the catchments C2 and C3.

3. Results and Discussion

General characterization of the hydrological data series

The historical series of daily precipitation and flow of the three experimental catchments have different extents because data records began in 2009 in the C1 catchment and in 2013 in C2 and C3. Although precipitation was the same for the three catchments, there were differences in the dynamics and values of flow and baseflow (Figure 3). These differences were expected as the hydrological response to precipitation events is influenced by vegetation characteristics, including management practices, and by the physical characteristics of the catchment (Brown, Zhang, McMahon, Western, & Vertessy, 2005; Sun et al., 2004), which differed between the catchments studied (Table 1, Figure 2).

The average daily flows recorded in the C1, C2 and C3 catchments were 0.55 mm, 0.27 mm and 0.58 mm, respectively. The shares of baseflow in the average daily flow were 79%, 55% and 70%, respectively, in C1 (0.43 mm), C2 (0.15 mm) and C3 (0.41 mm). Thus, it can be noted that, although the average daily flow followed the decreasing order C3>C1>C2, the daily average values of baseflow followed the decreasing order C1>C3>C2. Although surface runoff is usually governed by the slope of the terrain, forests commonly reduce surface runoff due to increased roughness (Kalantari et al., 2014), and subsurface runoff can be increased by maintenance or improvement in the infiltration capacity of forest soils (Neary, Ice, & Jackson, 2009; Price, 2011), thereby increasing the chances of underground recharge. For this reason, although the C1 catchment has higher average slope compared to the others (Table 1), it had greater share of baseflow in the flow.

In relation to the concentrations of total suspended solids in the catchments (Figure 4), C3 had a higher and significantly different ($p<0.05$) median (5.7 mg L^{-1}) compared to the medians of C2 (4.0 mg L^{-1}) and C1 (3.5 mg L^{-1}). Regarding nitrate concentrations, the three catchments differed significantly ($p<0.05$), and C2 had the highest value (0.60 mg L^{-1}), followed by C3 (0.50 mg L^{-1}) and C1 (0.30 mg L^{-1}) (Figure 4). The C1 catchment had the lowest values for the two parameters analyzed. Differences between the studied

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catchments were expected because even catchments that are close and similar may have different water quality parameters as a result of small variations in geology, soils or shading of streams, for example (Binkley & Brown, 1993; Feller, 2005). Nevertheless, in general, the concentrations of total suspended solids and nitrate recorded in the three catchments (Figure 4) are within the range of values reported in studies conducted in catchments with forest management (Aust & Blinn, 2004; Baillie & Neary, 2015; Binkley & Brown, 1993; Grace, 2005) and corroborate the fact that usually the water quality of forest landscapes is superior to that of other types of land use, such as agricultural use (Binkley, Burnham, & Lee Allen, 1999; Boggs, Sun, Jones, & McNulty, 2013; Da Silva et al., 2007; Diaz-Chavez, Berndes, Neary, Elia Neto, & Fall, 2011; Grace, 2005; Sun et al., 2004; Van Dijk & Keenan, 2007).

Hydrological regime of adult plantations

The presence of forest plantations with different ages in the C1 catchment resulted in a forest mosaic with annual mean ages ranging from 10.3 to 16.2 years considering the period of 10 water years (2009 to 2019). The mean age of the catchment is higher than the cutting age normally adopted in the management of Eucalyptus planted forests in Brazil, which is 6 to 8 years (Gonçalves et al., 2013). The dynamics of the annual values of the indicators analyzed in relation to the annual mean age of forest plantations present in the C1 catchment can be observed in Figure 5.

The mosaic of forest plantations analyzed with mean ages between 10 and 16 years showed a trend of stability in relation to the hydrological regime and water quality. The results confirm the greater stability of the flow over the years in forest mosaics (Ferraz et al., 2013), resulting from the absence of clearcutting in total area of the catchment. This trend of flow stability over time could be a "buffer effect" of the presence of forest plantations at different ages (Ferraz et al., 2019). A characteristic of the mixture of ages would be to balance the water use, making the higher consumption of young plantations compensate for the low consumption of older plantations, since the higher water consumption would be observed in the first years of development (Almeida, Soares, Landsberg, & Rezende, 2007). Thus, in a forest mosaic, water consumption is expected to be lower than that observed in forest plantations with commercial rotation (less than 8 years).

It was expected to find a reduction in water use at more advanced mean ages of the forest mosaic, as observed in older forest plantations, due to the "plantation effect" (Calder, 2007; Zhang, Vertessy, Walker, Gilfedder, & Hairsine, 2007). However, the water yield observed in the C1 catchment (0.08 to 0.20) is in the upper range of variation of the values found for commercial eucalyptus plantations in Brazil, from 0.05 to 0.11 (Ferraz et al., 2019). Thus, the forest mosaic would not represent a reduction in water use by the forest plantation. However, the short period of time analyzed and the low variation of the mean age of the mosaic did not allow us to analyze the variation of water use at the catchment scale in mosaics of planted forests with more advanced ages, so specific experiments with this objective are still needed.

The C1 catchment presents a large share of the baseflow in the flow, with baseflow index (BFI) from 75% to 83% (Figure 5). The BFI observed may be one of the benefits of longer rotations on water resources compared to younger plantations (Jones & Post, 2004). In catchments with mosaic of young and adult forests, there is a greater storage of water in the soil, which would be related to the "sponge-effect-hypothesis" (Ogden, Crouch, Stallard, & Hall, 2013). This effect may be the result of greater protection of soils by forests and improvement of soil characteristics (Neary, Ice, & Jackson, 2009) in areas of forest mosaic when compared to areas that undergo clearcutting at very short intervals.

Regarding water quality, the mean annual concentration of total suspended solids ranged from 2.0 mg L^{-1} to 11.3 mg L^{-1}; and the mean annual nitrate concentration ranged from 0.14 mg L^{-1} to 0.93 mg L^{-1}(Figure 5). It was possible to note a trend of reduction in the concentrations of suspended sediments and nitrate, which is expected due to the absence of clearcutting in total area and forest management carried out in small portions of the catchment, a result similar to that observed in other studies (Cassiano, Salemi, Garcia & Ferraz, 2020; Ogasawara, Santos, Cassiano, Wemple, & Ferraz, 2020; Riekerk, 1983; Tremblay, Rousseau, Plamondon, Lévesque, & Prévost, 2009). Thus, despite the maintenance of water use compared to commercial plantations, the results indicate that the benefits of forest mosaic may be related to the maintenance of the

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hydrological processes of infiltration and percolation, which are essential for soil and water table recharge and for the control of surface runoff and erosion.

Hydrological effects of forest implantation

After 2016, the predominant land use in the C2 and C3 catchments was modified, respectively, to native vegetation (restoration through the planting of native tree species) and to commercial *Eucalyptus*plantation, as shown in Figure 2. Table 3 shows the precipitation, flow, evapotranspiration and BFI data recorded in the following two water years (2017/2018 and 2018/2019) in the C2 and C3 catchments, and in the C1 catchment, which did not show a change in the predominant land use. Based on the mean values, it can be noted that C3 had higher flow and lower evapotranspiration, while C2 had the lowest value of BFI; it is important to highlight that the annual precipitation of the two years analyzed (1796 mm and 2051 mm) was higher than the average annual precipitation of the region (1319 mm).

Due to the rapid growth of planted forests (West & Mattay, 1993; Whitehead & Beadle, 2004) and the increase in leaf area index in the first years (Almeida et al., 2007), the initial hypothesis was that the C3 catchment would have the highest evapotranspiration rates and lowest values of flow, as already evidenced in other studies with eucalyptus forests (Calder, Rosier, Prasanna, & Parameswarappa, 1997; Farley et al., 2005; Scott, 2005). However, there is evidence that peak consumption of planted forests probably occurs after the third year of growth (Forrester, Collopy, & Morris, 2010; Scott & Lesch, 1997), which suggests that the moment of greatest effect of the planted forest was not analyzed.

Another important point to be considered is the presence of native vegetation in 44% of the C2 catchment near the stream and that was not modified in the years analyzed. This proportion of forest cover could explain the water use in this catchment, which may be related to the presence of a developed root system (Christina et al., 2011) and its proximity to the water table (Salemi et al., 2012). Considering the contribution related to the area occupied by each cover to the average ET observed in the catchment and assuming that the ET/P of the native vegetation near the watercourse is equal to 1; in C3 (ET/P = 0.83), the 13% of native vegetation (ET/P=1) would indicate an ET/P of 0.80 in the rest of the area (87%) under eucalyptus plantation. In C2 (ET/P = 0.94), with 48% of native vegetation (ET/P=1), the value would indicate an ET/P of 0.87 in the rest of the area (52%) under native vegetation. In this case, it is reasonable to think that the proportion of native forest vegetation in C2 may be influencing the ET rates found, as observed in other studies (Salemi et al., 2012; Zhang, Sun, Shi, & Feng, 2012).

On the other hand, it is important to observe that the C2 catchment had the lowest values of BFI compared to the others, and C1 had the highest values. Since BFI reflects the physical characteristics of the catchment (e.g., geomorphology) (Price, 2011), it is possible to assume that C2 has different geological and physical characteristics, which could influence the observed results, so forest cover is not the only factor influencing the hydrological processes of this catchment (Brogna et al., 2017; Chandler, 2006; Price, 2011).

Through the flow duration curves of the daily flow data (Figure 6), it is possible to observe that the C3 catchment stands out from C1 and C2. The daily flow values of C3 are higher along the entire length of the flow duration curve, and the little pronounced difference between the minimum and maximum values of flow gives the curve a flatter shape, which would indicate a smaller variation in the flow data in this catchment. On the other hand, the C2 catchment has the lowest values of flow and a more angled shape for the flow duration curve, due to the more pronounced difference between the minimum and maximum values of flow (Figure 6). These characteristics of FDC are being influenced by both the physical properties of the catchment and land use (Smakhtin, 2001; Zhang et al., 2012). Studies conducted using the ratio of maximum and minimum FDC indicated lower effects on hydrological processes in catchments that had lower rates between maximum and minimum, such as C3 and C1 (Brogna et al., 2017; Strauch, MacKenzie, Giardina, & Bruland, 2015).

Thus, the comparison between the indicators Q_{10}, Q_{50} and Q_{90} obtained for the three catchments (Figure 6) demonstrates that the greatest differences were detected between C2 and C3, with highlight for the Q_{90}value of C3, which was 75% higher than that of C2. Greater relative effect on minimum flow rates (Q90) has also

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been observed in other studies, which found a greater relative difference between the minimum flows for changes in land use of the catchment (Brown, Western, McMahon, & Zhang, 2013; Brown et al., 2005; Lane, Best, Hickel, & Zhang, 2005).

In relation to the catchment with mosaic (C1), it is important to note that it had maximum values lower than those of C3 (47%) and a smaller difference in minimum values (38%) compared to C2. The mosaic as an alternative of forest management was discussed in greater detail in item 3.2; however, it is worth mentioning that the results of this item also indicate that, despite a lower water yield, the catchment would be maintaining the hydrological processes (BFI and Q90), as demonstrated in other studies with mosaic (Ogden et al., 2013).

The monthly values of the Q/P ratio obtained for the three catchments show that C3 (0.16) differs significantly ($p<0.05$) from C1 (0.10) and C2 (0.10) (Figure 7). This significant difference in the Q/P ratio reaffirms the results found of higher water yield in C3 compared to the other two catchments; despite the implementation of the eucalyptus forest, there were no negative effects in the first years.

Similarly, the catchments differ significantly ($p<0.05$) from one another in relation to the concentration of total suspended solids, and C3 has the highest concentration (5.3 mg L^{-1}) and C1 has the lowest concentration (2.3 mg L^{-1}) (Figure 7). These differences between the catchments may be related to the management carried out in C3 (plantation), but also the higher precipitation in the period and water yield may have resulted in a higher concentration of solids. Forest management, such as harvesting and planting, has the potential to influence the concentration of solids (Baillie & Neary, 2015; Grace, 2005), but the high water yield in C3 may have contributed to the increase in solids. The concentrations found in the catchments are similar to those reported in studies carried out in planted forests (Câmara & Lima, 1999), and the trend is the decrease in concentrations with the growth of forests (C2 and C3) (Feller, 2005).

Differently, in relation to nitrate, the C2 catchment has the highest concentrations (0.49 mg L^{-1}) and differs significantly ($p<0.05$) from C1 (0.40 mg L^{-1}) and C3 (0.43 mg L^{-1}) (Figure 7). The highest NO_3concentration in C2 may be the result of both lower value of flow, since the lower the amount of water, the higher the concentration, and the demand for this nutrient by the forests planted in C1 and C3 (Laclau et al., 2010).

Effects of coppice and forest plantation

The analysis of the ratio between flow and monthly precipitation showed significant differences ($p<0.05$) between the period that the predominant land use in the catchments was coppice and the period with forest plantation (Figure 8). In the C2 catchment, the Q/P ratio was twice as high in the period with forest plantation compared to the period with coppice (from 0.03 to 0.06), and in the C3 catchment the Q/P ratio was three times higher (from 0.05 to 0.15). The baseflow index (BFI) showed the same trend, with higher values in the period with forest plantation (61% and 77% for C2 and C3, respectively) compared to the period with coppice (39% and 45% for C2 and C3, respectively).

Coppicing has been used as an alternative with lower costs of implementation, leading to lower costs for establishing the new forest (Viana, Hoeflich, Morozini, & Schwans, 2015) and even reducing the erosive effects of soil tillage (Cinnirella, Iovino, Porto, & Ferro, 1998). In this study, we observed that the water use in the coppice system was higher than in the plantation system, corroborating other studies that also reported higher water consumption by coppice management in forest plantations (Dimitriou, Busch, Jacobs, & Schmidt-Walter, 2009; Drake, Mendham, White, Ogden, & Dell, 2012).

However, it should be noted that precipitation in the regrowth period (2014-2016) was lower than in the planting period (1830 mm/year between 2014 and 2016; and 2040 mm/year, between 2017 and 2019), which might have influenced the higher flow observed in the plantation. Despite that, the difference in flow was on average 150% between the different managements, while the difference in precipitation was 11%, reinforcing the possibility of higher consumption by the regrowth regime.

The greater water use by the regrowth could be explained by the root system already developed in subsurface, which would facilitate the access to water, especially in regions with water deficit, as is the case of the study

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area (Laclau et al., 2013). Although the system brings economic benefits with often equivalent yields in terms of biomass production (Gonçalves, Stape, Laclau, Bouillet, & Ranger, 2008), the results indicate that, in critical regions in terms of water availability or conflicts, the abandonment of this technique can be used as an alternative to reduce the hydrological effects of plantations (Ferraz et al., 2019).

The concentrations of total suspended solids and nitrate were significantly different ($p<0.05$) in the periods analyzed in the two catchments. The concentrations of both total suspended solids and nitrate were higher in the period in which coppice was the main land use in the catchments (Figure 8). The concentrations were expected to be higher for the plantation regime, which has soil tillage and greater possibility of nutrient transport than in coppice (Cinnirella et al., 1998). However, it is possible that the two systems have similar effects on water quality and the differences observed might have occurred due to the higher precipitation in the plantation period, causing a reduction in nutrient concentration due to the effect of greater dilution in the period.

Upcoming challenges of continuous monitoring

This study brought the results of 3 paired catchments under different forest covers, enabling the understanding of the effects of forest management on hydrological processes. Like the classical studies conducted in Coweeta Hydrologic Laboratory (Elliott & Vose, 2011) or Hubbard Brook experimental forest (Campbell et al., 2019), the studies conducted at Itatinga Experimental Forest Station bring relevant information for the management of forest plantations in the tropical region.

The maintenance of these long-term projects, with constant investments in equipment maintenance, data collection and analysis, continues to be a challenge not contemplated in short-term research projects. On the other hand, the studies demonstrate the importance of obtaining long series of hydrological data, due to the large annual variation observed in precipitation, the interannual influence of hydrological processes and the needs for calibration, consistency adjustments and corrections of possible failures in data collection.

Thus, the results demonstrate the need for further long-term studies that include, for example, the hydrological effects of forest management at advanced ages (more than 20 years), when it is expected that there may be a reduction in water use due to the smaller annual increment in biomass (Kuczera, 1987; McCulloch, 2007; Scott & Prinsloo, 2008).

Although we observed greater flow stability in mosaic plantations of advanced ages, confirming what was proposed by (Ferraz et al., 2013), the fact that no differences were observed between the water use of plantations at ages between 2 and 7 years (Best, Zhang, McMahon, Western, & Vertessy, 2003) and even in plantations with a mean age between 10 and 16 years (this study) may indicate the need to define other strategies to reduce water use in commercial plantations in areas with water deficit.

It was also noted the information gap on inter-cycle effects of plantations because, due to the short and intense cycles used in forest plantations, the results demonstrate the possibility of interference of a cycle in the subsequent one, where the depletion of soil water by the previous cycle may intensify the hydrological effects of the following cycle (Christina et al., 2016; Rodríguez-Suárez, Soto, Perez, & Diaz-Fierros, 2011), and recommendations for longer fallow time between cycles may be a recommendation for critical regions with the aim of improving soil recharge (Christina et al., 2016).

4.Conclusions

The results of monitoring in the paired catchments showed that the different forest management regimes mainly influenced the annual flow and the hydrological regime of the streams. Mosaic management with longer cycles (mean age between 10 and 16 years) showed better flow stability and higher water quality, but water use similar to that obtained with shorter cycles (between 5 - 7 years), indicating that this management alternative may not be sufficient to increase downstream water availability. In the short-cycle management, there were greater effects on flow in the coppice management, indicating that this system can aggravate conflicts for water use in regions with low water availability.

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Due to the short cycles used and the rapid response of fast-growing plantations to water availability, only comparative studies with paired catchments under the same environmental conditions seem capable of explaining the effects of forest management on the hydrological regime of streams.

Acknowledgements

This study was supported by FAPESP (grant no. 2013/22679-5; 2016/02877-5), CNPq (grants: 420423/2016-8; 306645/2018-1). We gratefully acknowledge the staff team of Itatinga Forest Science Experimental Station from ESALQ/USP.

Data Availability Statement

The data that support the findings of this study could be available from the corresponding author upon reasonable request.

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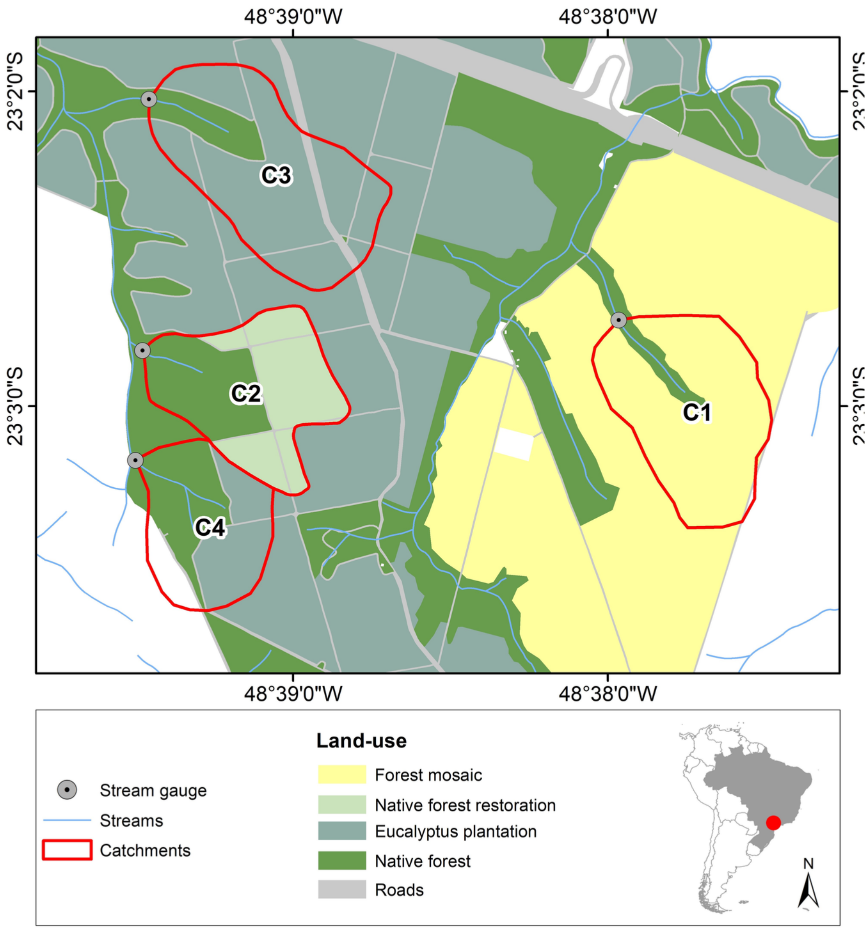

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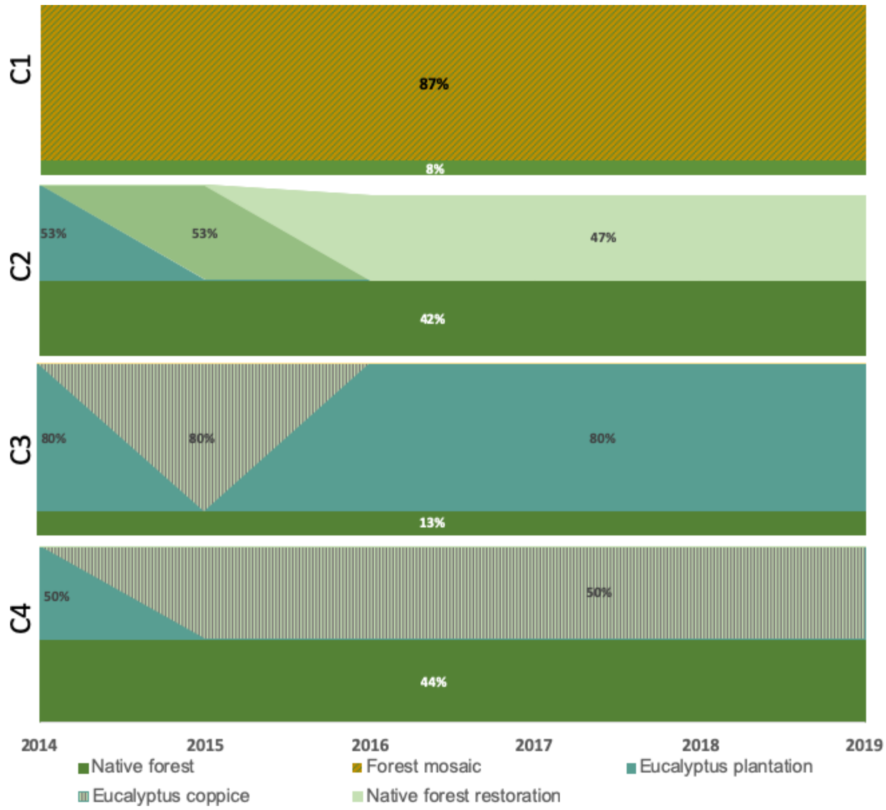

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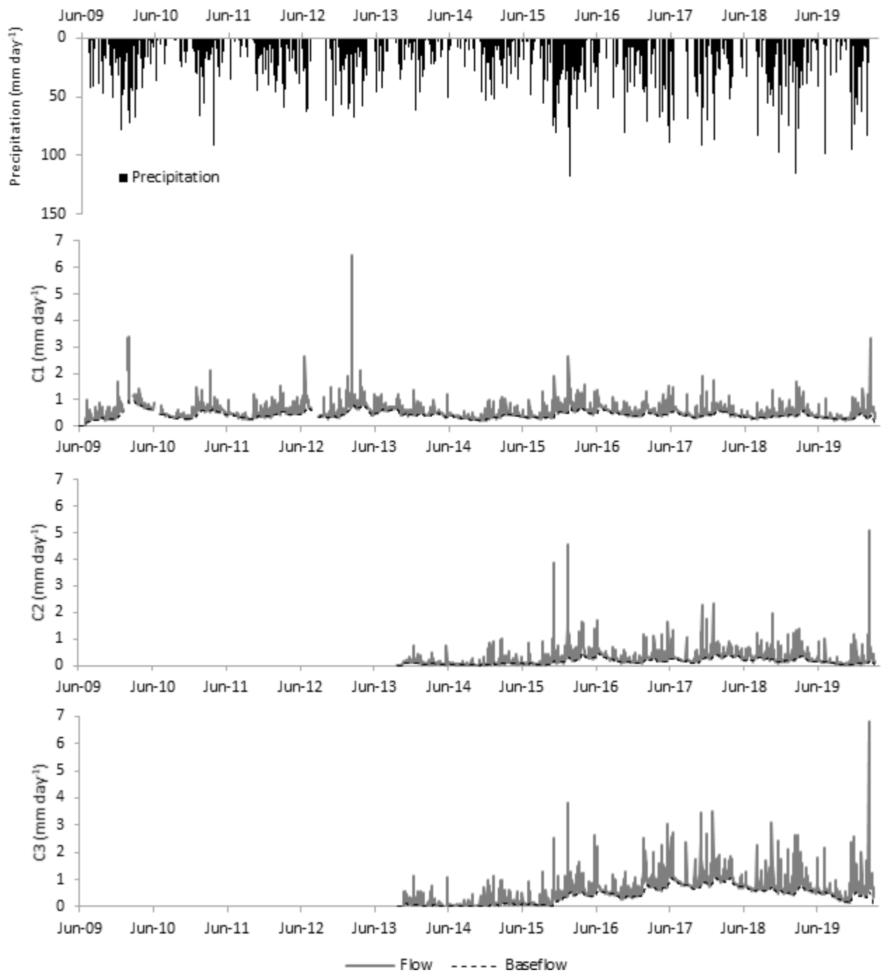

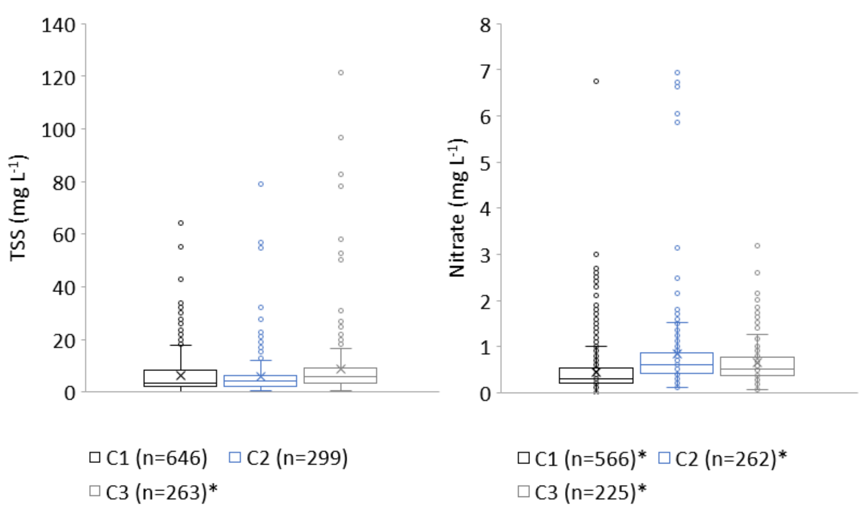

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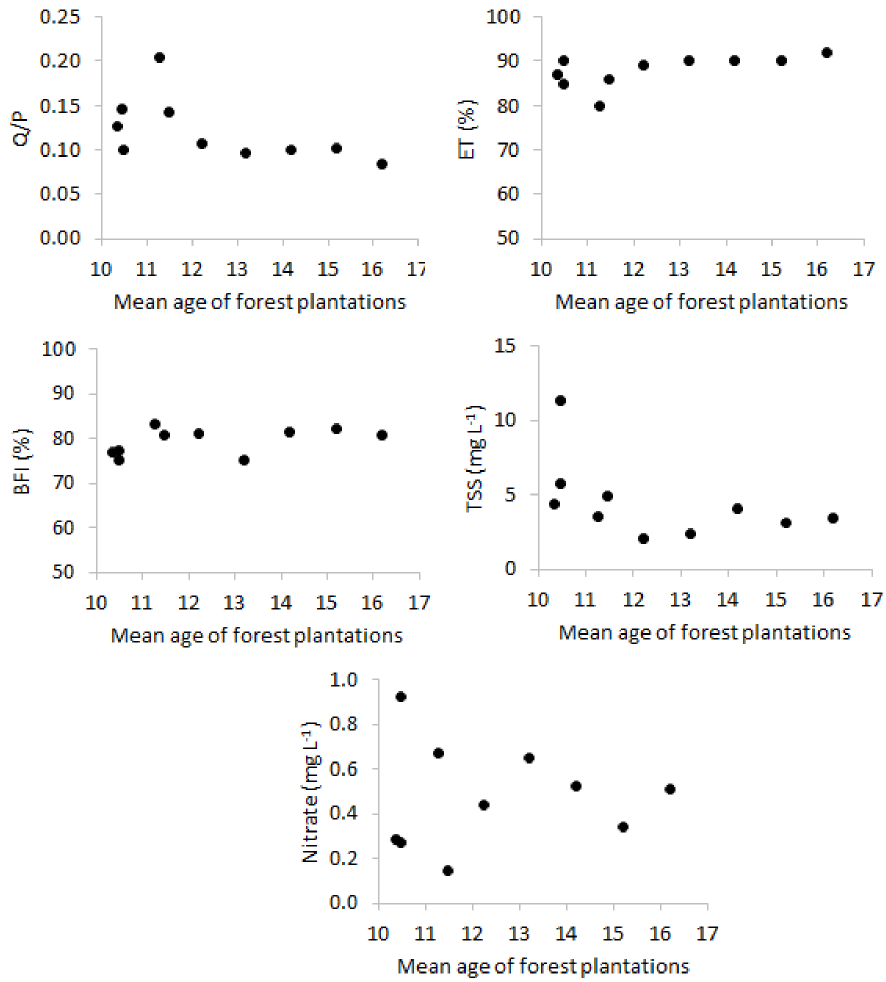

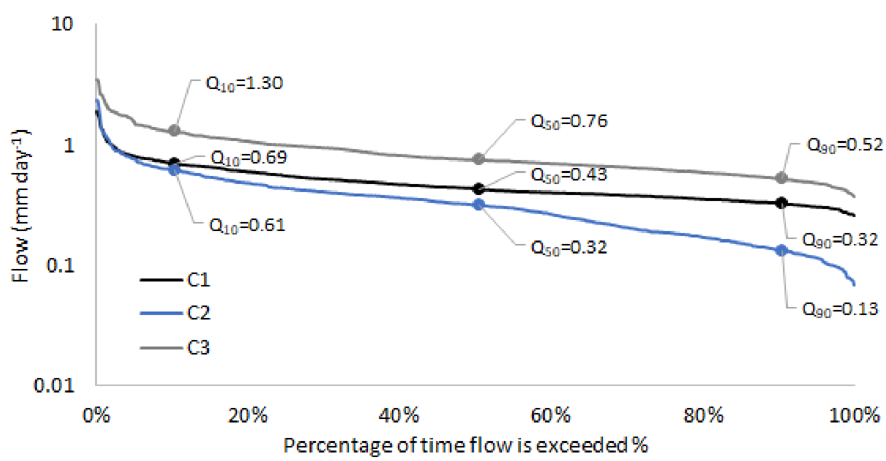

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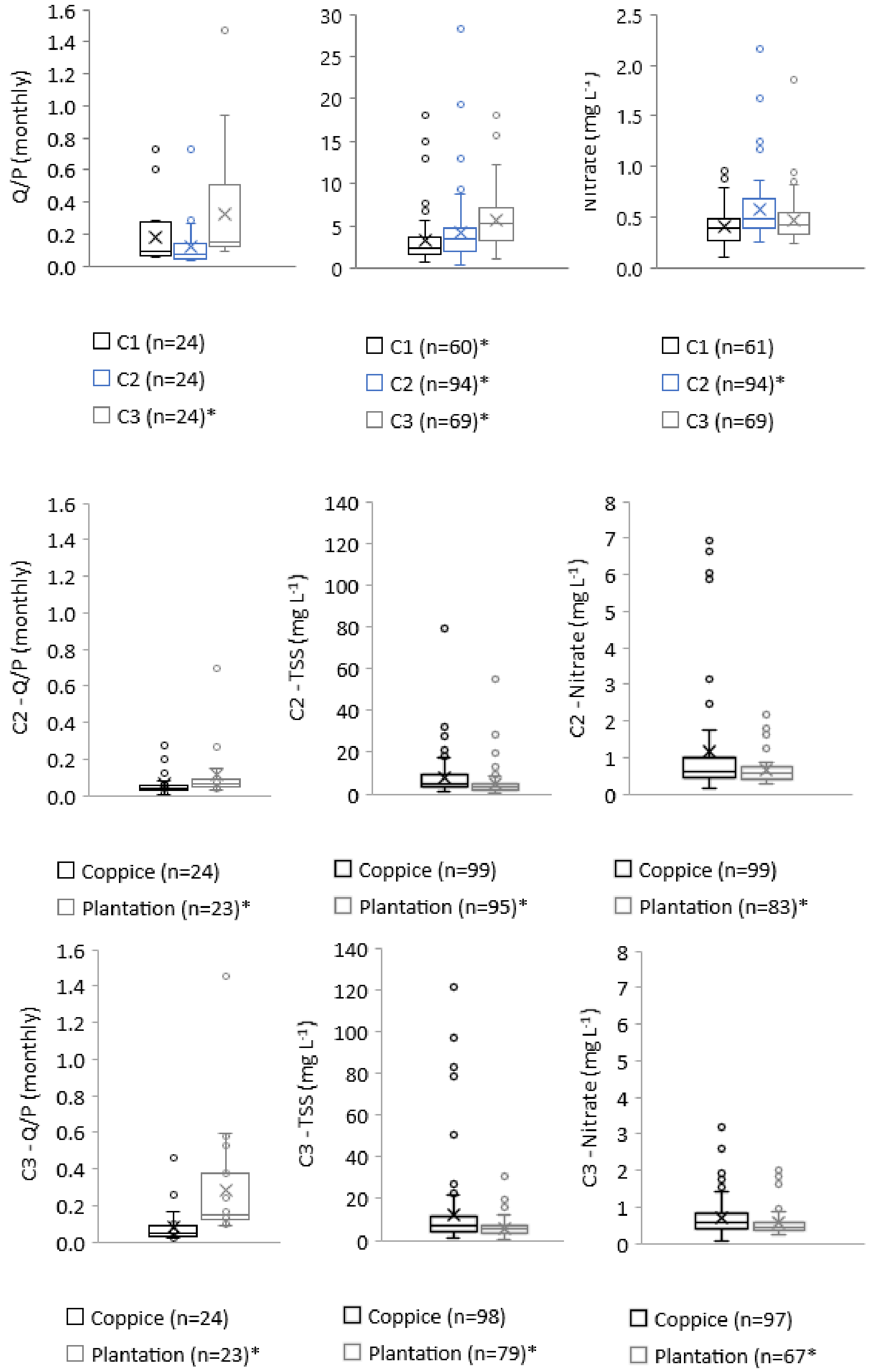

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