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Research Article

Fast-growing forest management to regulate the balance between wood production and water supply

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ABSTRACT: Increasingly, fast-growing forest plantations are able to support the wood supply but may simultaneously reduce water availability. The trade-off between wood production and water supply is more evident in areas with low water availability, high seasonal variation, or high water demand from local communities. The management regime adopted in forest plantations can either increase or reduce this trade-off. Thus, we assess herein the water and wood supply under different fast-growing forest plantation management regimes to understand how forest management practices can balance the provision of these services. The study was conducted at two catchments with a predominance of fast-growing forest plantations, namely, the mosaic management catchment (MMC) and the intensive management catchment (IMC). Rainfall and streamflow were monitored for three water years. Hydrological indexes were calculated to assess the hydrological regime of both catchments, and make inventories of the forest to assess forest growth rates. MMC had streamflow coefficients, baseflow index and baseflow stability higher than those of IMC. Mean annual wood increment was 32.73 m^3 ha^{-1} yr^{-1} in MMC, with a mean age of 15 years, and 44.40 m^3 ha^{-1} yr^{-1} in IMC at coppice in the second year. MMC hydrological indexes remained stable over the period studied, while in IMC the hydrological indexes were affected by climatic variations, mainly in drier years. MMC showed potential for supplying both water and wood. However, in IMC there was a trade-off between wood supply at the expense of the water supply. Thus, the intensity of fast-growing management can be adjusted to achieve a balance between water and wood supply on a catchment scale.

Keywords: provision services, forest plantation, hydrological regime, climate change

Introduction

Land use change on a catchment scale has a direct influence on water resources, especially in the case of the establishing of a new forest or the harvesting of an existing one (Brown et al., 2005; Jackson et al., 2005; Neary, 2016). Forest management modifies water provision throughout the forest rotation (Scott and Prinsloo, 2008; Van Dijk and Keenan, 2007) and the provision of ecosystem services may differ according to forest management practices (Baral et al., 2016). The establishment of fast-growing forest plantations can reduce streamflow dramatically (Jackson et al., 2005); however, it contributes to water recycling in the atmosphere and wood production (Christina et al., 2017), resulting in an ecosystem service trade-off.

Eucalyptus plantations in Brazil occupy 6.97 million hectares. These forest plantations are managed in short rotation cycles of less than ten years, with mean annual increments of 35.3 m^3 ha^{-1} yr^{-1} (IBA, 2020), reaching 62 m^3 ha^{-1} yr^{-1} at sites without water limitations (Stape et al., 2010). In fact, water availability is probably the main resource controlling forest productivity in tropical regions (Stape et al., 2004; Santana et al., 2008; Stape et al., 2010), as it is directly related to annual rainfall (Zhang et al., 2001). There are projections of increases or decreases in mean annual rainfall for the different regions of Brazil (IPCC, 2021). In modeled scenarios of rainfall reduction, a decrease in catchment streamflow (Feikema et al., 2012) was observed. In forest plantations, silvicultural practices can mitigate or even accelerate the effects of climate change on water supply (Ford et al., 2011).

An adaptive management strategy for fast-growing forest plantation can be formulated to align the wood and water supply, mainly in places with water conflict or in water-limited regions (Calder, 2007; Ferraz et al., 2019). The use of more heterogeneous management, for example, with uneven age stands in the catchment may reduce variations in groundwater levels throughout the year (Almeida et al., 2007), thus, stabilizing the streamflow while maintaining forest productivity (Ferraz et al., 2013). Balancing wood production and water supply may be necessary to meet the new demands of a developing society and have more resilient forest plantations to tolerate climate change. In this study, we assess water and wood supply under different fast-growing forest plantation management regimes to understand how forest management practices can balance the provision of these services.

Materials and Methods

Study area

The two catchments studied were located in Itatinga-São Paulo/Brazil (23°03′ S, 48°39′ W, altitude of 850 m)

(Figure 1). The climate in the region is Cwa, according to Köppen's classification, with dry winters and hot summers (Alvares et al., 2013) and mean annual rainfall of 1.372 mm (CEPAGRI, 2016). The aridity index (PET/P) in the municipality of Itatinga is 0.7 slightly below the threshold of 0.76 that would represent a risk to water availability due to the presence of fast-growing forest plantations (Ferraz et al., 2019).

The water year was determined with reference to the normal climatological water balance available for Itatinga-São Paulo/Brazil (Sentelhas et al., 2003). The water year starts in the month following the month with the greatest water deficit in the soil, which coincides with the month with the lowest streamflow (Gordon et al., 2004). Thus, the water year for Itatinga is from Sept to Aug.

Soil types of catchments are Hapludox Typic and Rhodic (Table 1), with texture varying from sandy loam to sandy clay loam, respectively (Gonçalves et al., 2012), with the same underlying geology (Sandstone from sedimentary rocks). Topographic conditions of both catchments are quite similar in terms of elevation range and slope (Table 1).

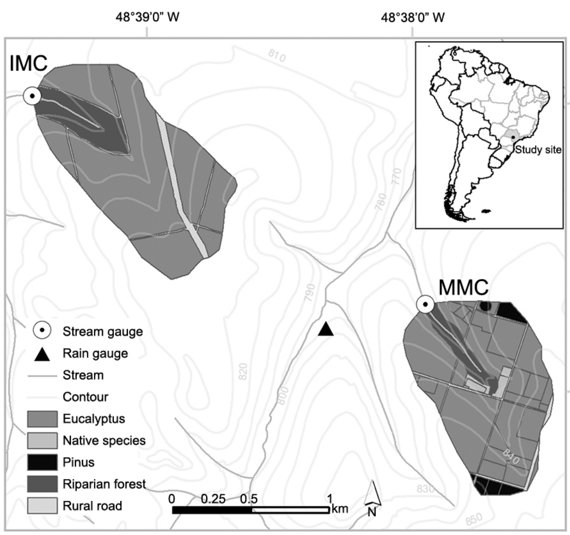

Figure 1 – Location and land use map of the Mosaic Management Catchment (MMC) and the Intensive Management Catchment (IMC).

The mosaic management catchment (MMC) has forest stands with different species and ages, mainly as a result of being an experimental area. The longest forest experiment in MMC was implemented in 1992 and the most recent in 2014. The main species in MMC is *Eucalyptus* spp., occupying 76 % of the catchment with different ages (Table 1).

Intensive management catchment (IMC) has a fast-growing forest management regime for pulp and cellulose production, with stands of the same clone of eucalyptus and even age (Figure 1), in which forestry operations are carried out on all stands concomitantly. The management is usually coppiced with a seven-year rotation period. The last harvest was in 2014, harvesting 80 % of IMC area, followed by eucalyptus regrowth. Both catchments have a native riparian forest occupying approximately 8 % and 12 % of MMC and IMC areas, respectively, which is protected by Brazilian Environmental Law and must be preserved without management (Table 1).

Hydrological dataset

Rainfall was measured continuously at 30-min intervals between catchments (Figure 1) with an automatic rain gauge (TR-5251) for three water years (1 Sept 2013 to 31 Aug 2016). The water years were 2013-2014 (WY13), 2014-2015 (WY14) and 2015-2016 (WY15). Annual rainfall was used to characterize each water year.

The streamflow was measured through an H-flume structure and automatic water level sensor (pressure transducer HOBO U20), at 15-min intervals in each catchment. The HOBO U20 sensors were installed in Oct 2013, 50 days after the beginning of the first water year (WY13). Missing data from this period were estimated by a linear function between the daily

Table 1 – Description of the Mosaic Management Catchment (MMC) and the Intensive Management Catchment (IMC).

<table>
<tr><th colspan="2"></th><th colspan="2">MMC</th><th colspan="2">IMC</th></tr>
<tr><td colspan="2">Area (ha)</td><td colspan="2">83.6</td><td colspan="2">101.2</td></tr>
<tr><td colspan="2">Mean slope (%)</td><td colspan="2">8.5</td><td colspan="2">5.5</td></tr>
<tr><td colspan="2">Minimum elevation (m)</td><td colspan="2">794</td><td colspan="2">779</td></tr>
<tr><td colspan="2">Maximum elevation (m)</td><td colspan="2">851</td><td colspan="2">841</td></tr>
<tr><td rowspan="6">Land-use (%)</td><td rowspan="4">Forest Plantation</td><td rowspan="4">87</td><td>9 % Pinus (> 21 years)</td><td rowspan="4">80.2</td><td rowspan="4">100 % even-aged Eucalyptus (< 7 years)</td></tr>
<tr><td>4 % Native (> 16 years)</td></tr>
<tr><td>57 % Eucalyptus (> 15 years)</td></tr>
<tr><td>30 % Eucalyptus (< 8 years)</td></tr>
<tr><td>Native Forest</td><td colspan="2">7.7</td><td colspan="2">12.5</td></tr>
<tr><td>Rural road</td><td colspan="2">5.3</td><td colspan="2">7.3</td></tr>
<tr><td colspan="2">Road density (m ha^{-1})</td><td colspan="2">49.5</td><td colspan="2">41.7</td></tr>
<tr><td rowspan="2">Soil type (%)</td><td>Typic Hapludox</td><td colspan="2">42.5</td><td colspan="2">100</td></tr>
<tr><td>Rhodic Hapludox</td><td colspan="2">57.5</td><td colspan="2">0</td></tr>
</table>

rainfall and daily mean streamflow data. Over the three water years, the sensors failed 11 % and 3 % of the time in MMC and IMC, respectively. The data series failures were filled with data from a backup water level sensor (Orpheus mini). Daily and annual streamflow (mm) were used to characterize the hydrological regime of the catchments.

Hydrological indicators

The water supply was characterized by the annual streamflow (Q), baseflow index (BFI) (Brogna et al., 2017), streamflow coefficient (Q/R), flow variability (Q10/Q90) and baseflow stability index (Q90/Q50).

The baseflow index (BFI) was calculated using the digital filtering method of Lyne and Hollick (1979) described by Grayson et al. (1996). The BFI was calculated from the daily streamflow in three passes with a filter coefficient of 0.925. The streamflow coefficient (Q/R) is the ratio between the annual amount of streamflow and the annual amount of rainfall.

Flow Duration Curves (FDCs) were drawn using daily streamflow for each water year and for the entire period studied. The daily streamflow data were sorted from largest to smallest, classified in frequency classes and plotted on a logarithmic scale (Gordon et al., 2004). The low flow (Q90), median flow (Q50) and storm flow (Q10) were extracted from the FDCs representing the flow values that were equaled or exceeded 90 %, 50 % and 10 % of the time, respectively. The ratio between Q10 and Q90 (Q10/Q90) was used to assess flow variability (Richards, 1990; Strauch et al., 2015) and the ratio between Q90 and Q50 (Q90/Q50) was used to calculate a baseflow stability index (Strauch et al., 2015).

Forest inventory

Wood production was estimated for one forest inventory in each catchment. The stands of the mosaic management catchment (MMC) were grouped by genus and age, and 40 random stratified sampling plots of 540 m^2 were selected (Table 2). The intensive management catchment (IMC) had five plots selected by simple random sampling (Table 2). The diameter at breast height (DBH) of all trees and the height of 15 trees were measured. A relation between the DBH and height was calculated for each plot to estimate the height of all trees, and the volume was computed based on the cylinder volume equation multiplied by a form factor of 0.5 (Oliveira et al., 1999). The mean annual increment (MAI) was calculated by dividing the volume (m^3 ha^{-1}) by the age of each group. For MMC, after computing the MAI per group, the MAI for the catchment was calculated by the average MAIs weighted by the occupied area of each group.

Results

Hydrological data

The first and last water years showed atypical rainfall (Table 3). The annual rainfall in WY13 was 34 % lower than the mean annual rainfall expected for the region (1,372 mm), representing an example of a dry year, with monthly rainfall below 100 mm in the summer. Conversely, in the WY15 it was 88 % higher than the mean annual rainfall, representing a wet year, with monthly rainfall of over 100 mm in the winter. The two water years preceding the study and WY14 had annual rainfall close to the mean annual rainfall.

Table 2 – Forest inventory for the Mosaic Management Catchment (MMC) and Intensive Management Catchment (IMC).

Genus	Age (years)	Sampling Plots	Volume	MAI	Area	Volume	Thinning/ Planting failure[a]
			m^3 ha^{-1}	m^3 ha^{-1} yr^{-1}	ha	m^3	%
Mosaic Management Catchment							
Pinus	26	3	335.86	12.92	2.84	954.70	23.3
Pinus	22	3	840.82	38.22	1.29	1087.80	50.0
Eucalyptus	21	3	525.08	25.00	6.41	3366.45	45.0
Pinus	21	3	785.78	37.42	2.42	1898.38	58.2
Eucalyptus	20	3	341.46	17.07	2.68	915.95	45.6
Eucalyptus	20	3	593.03	29.65	11.00	6525.55	21.1
Eucalyptus	19	3	305.72	16.09	9.48	2898.72	35.2
Eucalyptus	19	3	469.44	24.71	9.56	4489.28	77.0
Native	16	1	155.22	9.70	2.60	403.04	64.4
Eucalyptus	15	1	425.13	28.34	2.64	1122.58	55.6
Eucalyptus	8	3	320.56	40.07	2.24	716.70	53.7
Eucalyptus	5	2	236.33	47.27	3.77	890.25	1.1
Eucalyptus and Acacia	5	3	273.66	54.73	5.64	1543.70	26.7
Eucalyptus	4	6	238.75	59.69	10.15	2423.35	15.9
Intensive Management Catchment							
Eucalyptus	2	5	88.81	44.40	81.15	7206.73	5.8

[a]Planting failure: difference between the number of trees planted and the number of existing trees.

The mean daily streamflow in the study period was 0.55 mm and 0.26 mm for MMC and IMC, respectively, with maximum values of 2.32 mm and 3.25 mm and minimum values of 0.18 mm and 0.00 mm, respectively (Figure 2A and B). The IMC had two days with zero flow at the end of WY13. The annual streamflow was higher in MMC for the entire study period (Table 3), although this difference has decreased over time, annual streamflow in MMC was 4.78 times higher than in IMC in WY13, and just 1.34 times higher in WY15.

Hydrological indicators

The streamflow coefficient (Q/R) was higher for MMC than for IMC in all water years (Table 3), it was five times higher in MMC than in IMC in the dry year (WY13). The Q/R for WY15 was half of that for WY13 in MMC, although the annual streamflow was 32 % higher in WY15. The IMC had a 75 % increase in Q/R, which corresponded to an increase of 370 % in annual streamflow, from WY13 to WY15.

Changes in BFI between water years have taken a different course in each catchment, and whereas BFI decreased in MMC over time, BFI increased in IMC (Table 3). The baseflow for the whole period (3WY) was 80 % and 56 % of total streamflow in MMC and IMC, respectively.

The stability of the hydrological regime of MMC is reflected in the baseflow stability and variability index (Table 3). MMC shows less variability in streamflow (Q10/Q90, average of 2.1) and more stability (Q90/Q50, average of 0.51) than IMC (averages of 10.5 and 0.14, respectively). WY15 brought more pronounced changes in IMC, increasing its stability, and decreasing its variability, approaching the hydrological regime of MMC. The variability index (Q10/Q90) was ten times higher for IMC compared to MMC, and the baseflow stability index (Q90/Q50) was three times lower for IMC compared to MMC for the entire period of study (3WY-1095 days) (Table 3). The differences between the hydrological regimes of the catchments are also presented through FDCs (Figure 3A, B and C). Despite the atypical rainfall years, the FDCs were very similar between water years for MMC (Figure 3A) while IMC shows steeper FDCs in WY13 and WY14.

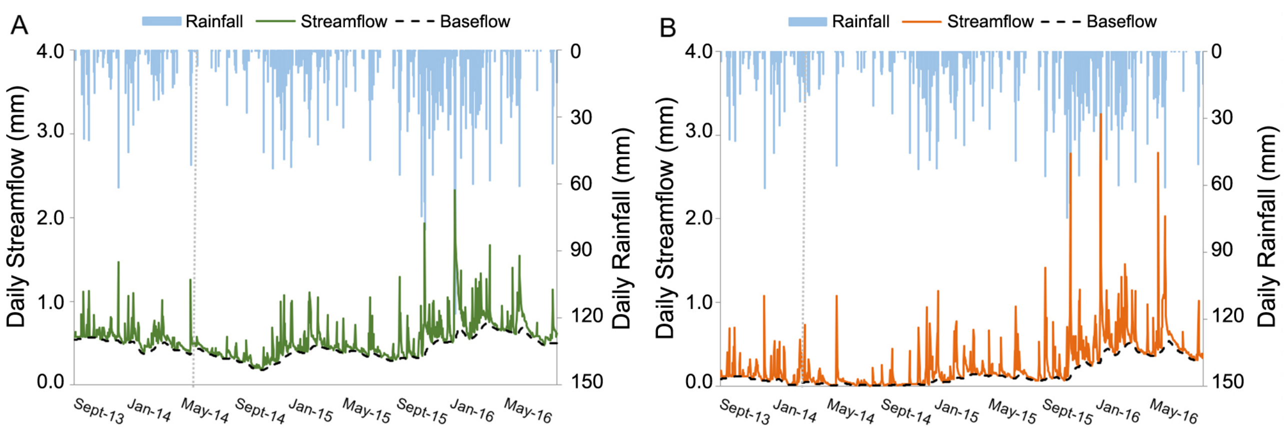

Figure 2 – Catchment hydrological regime: A) Mosaic Management Catchment (MMC), 14 % planted in June 2014 (perpendicular dashed line), and B) Intensive Management Catchment (IMC), 80 % harvested in Apr 2014 (perpendicular dashed line).

Table 3 – Rainfall (R), annual streamflow (Q), streamflow coefficient (Q/R), baseflow index (BFI), storm flow (Q10), median flow (Q50), low flow (Q90), flow variability (Q10/Q90) and baseflow stability (Q90/Q50) of the Mosaic Management Catchment (MMC) and the Intensive Management Catchment (IMC) for water years 2013-2014 (WY13), 2014-2015 (WY14), 2015-2016 (WY15) and for the tree water years (3WY).

	MMC				IMC			
	WY13	WY14	WY15	3WY	WY13	WY14	WY15	3WY
R (mm)	910.4	1386.8	2587.6	4884.8	910.4	1386.8	2587.6	4884.8
Q (mm)	193	156.7	255.5	605.2	40.4	57.5	190.1	288.0
Q/R	0.21	0.11	0.10	0.12	0.04	0.04	0.07	0.06
BFI (%)	85.2	79.3	76.6	80.13	43.5	46.4	61.8	56.19
Q10 (mm)	0.66	0.59	0.96	0.80	0.23	0.30	0.85	0.61
Q50 (mm)	0.63	0.55	0.89	0.53	0.18	0.26	0.74	0.15
Q90 (mm)	0.37	0.27	0.39	0.33	0.02	0.02	0.18	0.02
Q10/Q90	1.76	2.18	2.45	2.43	13.03	13.74	4.68	25.73
Q90/Q50	0.60	0.50	0.44	0.63	0.10	0.09	0.24	0.16

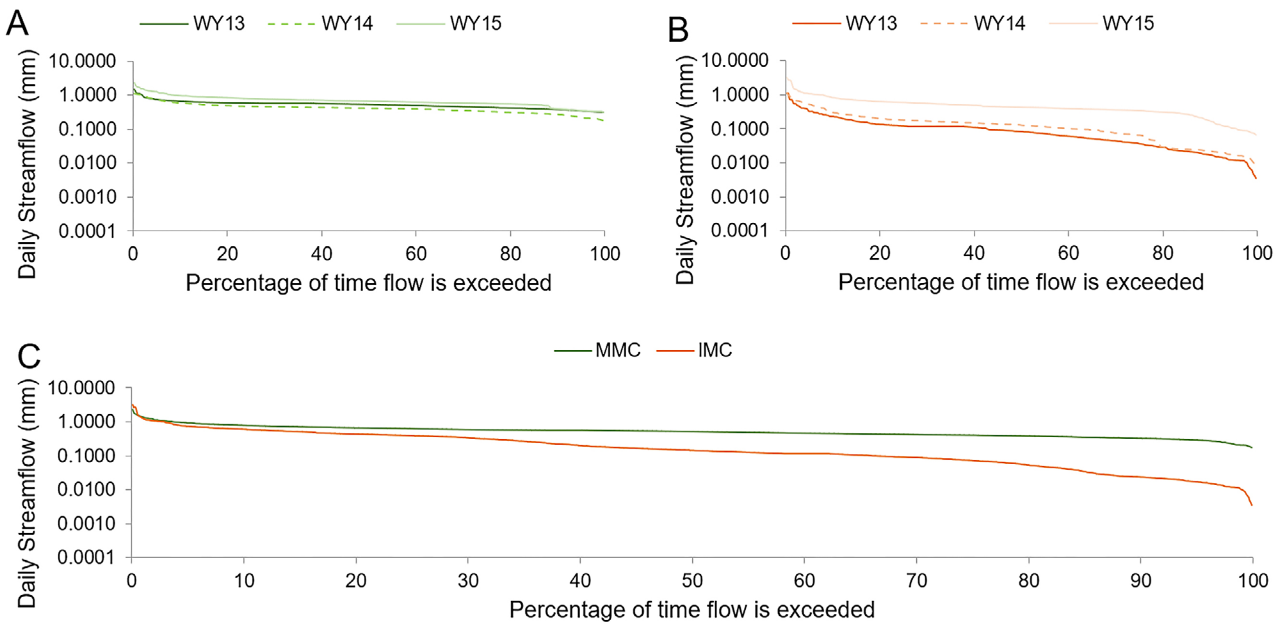

Figure 3 – Catchment Flow Duration Curves (FDC), A) Mosaic Management Catchment (MMC), B) Intensive Management Catchment (IMC) (WY13 = water year 2013-2014, WY14 = water year 2014-2015, WY15 = water year 2015-2016), and C) Flow duration curves for the three water years (3WY).

Wood production

The MMC forest inventory had an estimated wood volume of 29,236 m^3 in 2018 (Table 2) which represents a mean annual increment (MAI) of 32.73 m^3 ha^{-1} yr^{-1}. The MAI in MMC groups ranged from 9.7 to 59.7 m^3 ha^{-1} yr^{-1}, in native and eucalyptus, respectively, and the mean age of MMC groups was 15 years. The IMC forest inventory by the second year of coppice regrowth was estimated at an MAI of 44.40 m^3 ha^{-1} yr^{-1}, which leads to an estimated volume of 25.22 m^3 for 2021 at the time of harvest.

Discussion

Water and wood supply at different forest management intensities

Water availability at MMC was higher than at IMC for the three water years. MMC had a streamflow coefficient higher than 10 %, being at the upper limit of the expected for catchments with fast-growing forest plantations in Brazil, which is 5 % to 11 % (Ferraz et al., 2019). Conversely, in IMC, the streamflow coefficient was less than 7 % in the three years of study, being 4 % in the first two years, which demonstrates a relatively high level of water use (Baral et al., 2013), even higher than that observed in other studies in Brazil (Cabral et al., 2010; Ferraz et al., 2019; Rodrigues et al., 2019).

The baseflow index is higher in MMC than in IMC during the period studied. The BFI usually reflects the effects of catchment geology (Smakhtin, 2001) although the catchments studied are in the same geological formation, on Oxisols (Gonçalves et al., 2012) the differences in BFI may be due to other factors. The soil water content in deep soils is controlled by topographic features, climate conditions, vegetation characteristics and management practices (Cao et al., 2018). Thus, vegetation characteristics such as planting density (Fang et al., 2016) and plant age (Wang et al., 2012) can affect water storage, and, consequently, the BFI in our catchments is probably affected by forest management intensity.

The FDCs were very similar over the three water years in the MMC, despite the differences in annual rainfall, which modified the storm flows, the FDCs were "flat", demonstrating a uniform streamflow response (Burt and Swank, 1992). Meanwhile, IMC curves were "steep" and more responsive to variations in rainfall and land cover changes, especially in the first and second water years. The Q90/Q50 and Q10/Q90 indexes confirm the flow stability and its low variability in MMC. When comparing the values of the indexes between catchments, the IMC has Q90/Q50 values at least twice as low as those of the MMC and Q10/Q90 values at least twice as high as those of the MMC, indicating a catchment with less stable and more variable streamflow. Thus, MMC presents greater regulation of its hydrological regime and water supply against rainfall variations and forestry operations compared to IMC, corroborating studies that suggest mosaic management may be an appropriate strategy for increasing flow regulation (Almeida et al., 2016 and Ferraz et al., 2013).

The management intensity in MMC changed from intensive to mosaic in 1997. Prior to 1997 MMC had an even-aged eucalyptus plantation, when this plantation was clear-cut, the streamflow of MMC increased (Câmara and Lima, 1999) and had a gradual decrease over the first years of growth in the new forest plantation, demonstrating a hydrological regime that follows the "plantation effect" (Ferraz et al., 2013). However, after more than 20 years of mosaic management MMC has a stable hydrological regime. A new hydrological equilibrium is expected to take eight to 25 years to effect a permanent change in forest cover (Brown et al., 2013). While at IMC, the dynamics of forestry operations with a short rotation (less than seven years) probably makes the hydrological regimes more responsive to land cover changes, as forest cover loss can lead to pronounced changes in streamflow (Zhang et al., 2017) and fast-growing forest plantation can reduce water resources in the first years of growth (Scott and Prinsloo, 2008).

MMC can supply water while producing wood. Both MMC and IMC catchments showed MAIs of 32.73 $m^3\ ha^{-1}\ yr^{-1}$ and 44.40 $m^3\ ha^{-1}\ yr^{-1}$, respectively. Despite the 36 % higher wood productivity in IMC, the MAI of MMC can be compared to the MAI of eucalyptus plantations in Brazil, of 35.3 $m^3\ ha^{-1}\ yr^{-1}$ (IBA, 2020), although certain stands of MMC had already been thinned, and part of its wood volume has been exploited over time.

We supposed that mosaic management (MMC) reached 100 % of hydrological services, and the intensive management (IMC) reached 100 % of MAI, as a hypothetical exercise (Figure 4). Relative hydrological service for IMC was calculated by the average of its hydrological indicators, compared to the average of those seen in MMC (100 %), and the indicators were: Q/R, BFI, Q10/Q90 and Q90/Q50 of the 3WY (Table 4). The same was ascertained for MAI, calculating the relative MAI for MMC, compared to IMC (100 %) (Table 4). Relative gains for hydrological services (61 %) were twice as high as the relative losses of MAI (26 %) when management changed from IMC to MMC. Interestingly, each hydrological indicator had a different sensitivity to mean annual increment reduction, but it is possible that small reductions in productivity, for example, through the selection of less productive genetic materials (Gonçalves et al., 2017), or with high water use efficiency (Hakamada et al., 2020), will promote substantial gains in hydrological services. In this case, as an example of intermediate management intensity, a small reduction in MAI can result in double the gains of hydrological services (Figure 4). It is worth mentioning that hydrological gains do not occur immediately after a management intensity change, as it takes some time for the catchment to reach a new equilibrium (Brown et al., 2013).

The proposal to adjust a balance between wood and water supply needs to be better tested as well as the magnitude of the tradeoffs in these resources, mainly

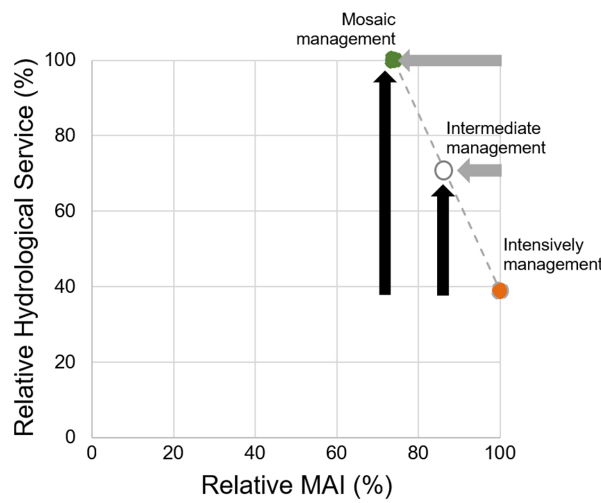

Figure 4 – Tradeoff between hydrological services and MAI due to changes in forest management intensity. Green circle represents Mosaic Management Catchment (MMC) and orange circle Intensive Management Catchment (IMC). When management intensity changed to mosaic management, lower relative losses in MAI (grey arrows) occurred when compared to relative gains in hydrological services (black arrow).

Table 4 – Relative gain of water and wood supply indicators from change management (Q/R = Streamflow coefficient, BFI = baseflow index, Q10/Q90 = flow variability, Q90/Q50 = baseflow stability, MAI = mean annual increment, MMC = Mosaic Management Catchment, IMC = Intensive Management Catchment).

Hydrological services indicators	MMC (100 %)	IMC	Proportion reached by lowest value	Relative gain from change management
			%	
Q/R	0.12	0.06	50	
BFI (%)	80.13	56.19	70	
Q10/Q90[a]	1 / 2.43	1 / 25.73	9	
Q90/Q50	0.63	0.16	25	
		Average	39	61
Wood production indicator	MMC	IMC (100 %)	Proportion reached by lowest value (%)	Relative gain from change management (%)
MAI ($m^3\ ha^{-1}\ yr^{-1}$)	32.73	44.40	74	26

[a]The indicator Q10/Q90 was inverted, once lower values were better, different from the other indicators.

under other climate and soil conditions. In this study, we present a case study based on only two catchments which can fuel the hypothesis that this relationship exists and can be managed. In addition, since the catchments are representative of a large part of the fast-growing forest plantations in Brazil being on Oxisols (Gonçalves et al., 2013) our results can serve as a premise for a change to conventional management regimes.

The MMC is located at a forest experimental area, with stands of different ages and different species, forming a mosaic that may be not replicable for the eucalyptus pulpwood chain. However, this shows that it is possible to produce wood with less intensive management than those regimes currently applied in even-aged eucalyptus plantations supporting water supply (Whitehead and Beadle, 2004). The reduction in forest management intensity is suggested for preserving water resources (Almeida et al., 2016; Ferraz et al., 2019; Hakamada et al., 2020), with the potential benefit of improving biodiversity conservation (Brockerhoff et al., 2008, 2013). However, the demand for these services at the local, regional, and global scale should be considered (Beier et al., 2015; Schulte et al., 2014) for assessing where reduction in management intensity is needed since it is important to find a balance between human needs and nature's ability to provide products and resources (Foley et al., 2005).

Water supply in atypical years

The annual rainfalls in WY13 and WY15 were different from the mean annual rainfall expected for the region, raising questions about the effects of atypical rainfall on the hydrological regime of the catchments. Despite the brevity of our study, analyzing three years only, the hydrological indicators demonstrate that the catchments had different hydrological regimes during this period. Thus, the differences in management intensities could influence their capacity for supplying water in a climate change scenario of increasing or decreasing rainfall and we have discussed its potential for changing catchment streamflow.

MMC has stands of different species and ages with forestry operations in progress gradually over time, in small areas, which should not affect its hydrological regime. This observation corroborates studies showing that changes in land use with afforestation or harvesting in less than 20 % of the catchment area cannot be detected through variations in streamflow (Bosch and Hewlett, 1982; Brown et al., 2005; Stednick, 1996). However, changes in annual streamflow were observed in MMC.

Annual rainfall was higher in WY14 than in WY13, but MMC had a decrease in annual streamflow in WY14. Although it is expected that the impacts of the previous year on water storage will be effectively removed by studying the water year (Brown et al., 2013), the low rainfall of WY13 may have influenced the decline in streamflow in WY14. Eucalyptus forest plantations can access the deep water table to meet their demand (Christina et al., 2011; Engel et al., 2005; Rodríguez-Suárez et al., 2011; Silva et al., 2020), and in deep soils (more than eight meters), the use of water by eucalyptus can be higher than the annual rainfall (Bruijnzeel, 2004; Calder et al., 1997; Christina et al., 2017). The catchment hydrological responses may be associated with their water storage capacity (Evaristo and McDonnell, 2019). Thus, well-managed catchments, or less intensively managed catchments, with deep soils, could have greater resilience in drought situations. Therefore, the effects of the low rainfall in WY13 led to a reduction in MMC streamflow in the following year but maintained water availability.

Furthermore, IMC has deep soils with water storage capacity; however, it was submitted to an intensive forest management regime. Eucalyptus harvesting in 80 % of the IMC area in an atypical year, with low rainfall (WY13), helped to maintain streamflow since the reduction in evapotranspiration in the catchment could assist the mitigation of drought (Beier et al., 2015). In a climate change scenario, an increase in the number of intermittent rivers is expected (Acuña et al., 2014) in regions prone to drought (Larned et al., 2010). In atypical drought situations, harvesting forest plantations presents an alternative for maintaining water availability on a catchment scale. Considering that productivity is directly related to water availability (Stape et al., 2004; Stape et al., 2010), eucalyptus regrowth may have used the soil water storage as the productivity estimated for IMC showed that the forest plantation had not been affected by the dry year. However, the use of water reserves by forest plantations could have decreased water storage, affecting the resilience of the catchment in subsequent years.

In contrast, in years with higher annual rainfall, water accumulates in deep soil reserves, becoming available to forest plantations (Bruijnzeel, 2004) in the future. We observed an increase in annual streamflow in both catchments in the third water year (WY15). Thus, an escalation in rainfall increased the water availability in the catchments regardless of the management intensity (Ford et al., 2011).

MMC showed flat flow duration curves in the three water years and better indexes than those of IMC, having no effect on water supply, even though water years have experienced climate extremes in relation to rainfall. Meanwhile, IMC had an increase of 18.3 % in baseflow index between WY13 and WY15 and the flow duration curve of WY15 was flatter than that of WY13, showing that IMC has the potential to have a similar hydrological regime to that of MMC, but its intensive management makes it susceptible to climate variations (Ford et al., 2011), mainly in relation to rainfall reductions. Furthermore, if the reductions in rainfall are below potential evapotranspiration it will increase the dryness index and impair water availability. Therefore, in a climate change scenario, in places with water conflicts, the use of less intensive management should be a priority, and aim to maintain water availability.

The annual rainfall and the rainfall distribution during the study were atypical for the region, which may have skewed our results. Catchment hydrological regimes are usually analyzed between similar water years since streamflow is generally determined by rainfall (Brown et al., 2005). The variation in rainfall could be seen as a limitation on our study; however, we saw it as an opportunity to understand the consequences of future climate changes.

The soils present in the catchments have different clay contents, Rhodic Hapludox soil present in 57.5 % of MMC is richer in clay content (32 %) than Typic Hapludox soil (16 %) present in both catchments. The capacity of water retention is controlled by soil texture (Geroy et al., 2011). Thus, MMC may have a greater capacity for water retention than IMC. The soil characteristics of MMC may have contributed to our results, especially to BFI. However, due to differences observed in water yield, which is probably not affected by soil texture, and the magnitude of differences in flow regulation (in MMC, Q10/Q90 is ten times lower, and Q90/Q50 is three times higher than in IMC), we supposed that management intensity is responsible for significant changes in the hydrological regime.

Conclusions

The intensive management of forest plantations with short rotations and coppice practices, as well as promoting wood supply, leaves the catchment´s hydrological regime dependent on the rainfall amount. In years with below-average rainfall, intensive management can accelerate water storage depletion in the catchment and reduce the water supply to other users. On the other hand, mosaic management can maintain both the hydrological regime of the catchment, even during water years with atypical rainfalls, and the wood supply, demonstrating that forest management can be a tool for regulating the water and wood supply on a catchment scale. This study suggests that relative gains in hydrological resources could be higher than losses in wood productivity, raising the hypothesis that adjustments in forest management intensity can balance these resources and needs to be better understood. Furthermore, it is essential that the intensity of management of wood supply through fast-growing forest plantations should be adequate to meet local demands for water to avoid conflicts over this natural resource.

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Authors' Contributions

Conceptualization: Ferraz, S.F.B. **Data acquisition:** Cassiano, C.C.; Moreira, R.M. **Data analysis:** Cassiano, C.C. **Design of methodology:** Ferraz, S.F.B.; Cassiano, C.C.; Moreira, R.M. **Writing and editing:** Cassiano, C.C.; Ferraz, S.F.B.

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