Forest Ecology and Management 301 (2013) 58–66

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Managing forest plantation landscapes for water conservation

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ARTICLE INFO

Article history:
Available online 17 November 2012

Keywords:
Brazil
Eucalyptus plantation
Catchment
Water use
Landscape management
Sustainable forest management

ABSTRACT

Forest ecosystems play an important role in water conservation yet forest plantations are considered detrimental because of their high water use. The current worldwide trends of reduction in natural forest and expansion of forest plantations increases the need for forest managers to contribute to water conservation, implementing management plans that integrate economic (productivity and growth), social (equity of access to water and land-use conflicts) and environmental (climate change and biodiversity impacts) factors. In this paper, we show examples of forest management alternatives at macro- and meso-scales that could contribute to improve water conservation in forest plantation landscapes. At the macroscale, we assess water use in different forest plantation areas in Brazil by analyzing the theoretical thresholds for the management of evapotranspiration. Then, using data from an experimental catchment, we modeled water yield reduction by a forest plantation over multiple years and assessed how different meso-scale forest plantation management alternatives affected water flow regulation. Results show that at a macroscale it is important to consider the natural climatic constraints of water availability. Evidence shows that forest plantations in the tropics use water according to its availability, and the appropriate choice of species/varieties and associated forest management options are crucial for water conservation. At the meso-scale we found that the proportion of native forest plays an important role in the reduction and regulation of water use, and therefore a system of mosaic management may be able to stabilize water flow across plantation landscapes.

1. Introduction

Forest plantations in Brazil currently cover about 7 million ha, and are represented mainly by *Pinus* and *Eucalyptus* (ABRAF, 2010). Most of these plantations supply the raw material for biofuels, pulp and paper and are generally managed on short rotations (i.e. fast-wood systems). Over the past 40 years, there has been an increase in the productivity of *Eucalyptus* plantations, which varies from approximately 12 m^3 ha^{-1} $year^{-1}$ to about 40 m^3 ha^{-1} $year^{-1}$ (Stape et al., 2001).

This increase in productivity and the expansion of planted forests requires adequate environmental support in terms of water and nutrients (Scott, 2005; Tetzlaff et al., 2007). There is a general consensus that the productivity of forest plantations is predominantly limited by water availability (Stape et al., 2004), as a lack of nutrients can be managed through fertilization.

However, the use of water by plantations has been the subject of intense discussion related to the high demand for water by fast growing plantations. Although there is sufficient information to clarify this controversy, its repeated occurrence indicates that the problem is far from resolved (Lima and Zakia, 2006; Scott and Prinsloo, 2008; Lima, 2011).

Concern regarding water consumption by plantations and its influence on productivity has stimulated research aimed at quantifying evapotranspiration on different scales and assessing the efficiency of water use (Stape et al., 2004), which can be defined as the efficiency with which trees are able to use available water to fix carbon dioxide (Binkley et al., 2004). The efficiency of water use is tied to the objectives of breeding programs, which are focused on the search for genetic varieties that are resistant to water stress and/or that have increased productivity with the same amount of water use (i.e. are more efficient) (Hubbard et al., 2010).

Information on the water use by plantations is undoubtedly important and necessary, but it seems obvious that it describes only part of a larger problem, as the issue of the expansion of forest plantations causing possible environmental impacts must, by its nature, also take into account interactions with the social and cultural factors involved in this transformation of the landscape. In the case of water, it is not enough to quantify how much is lost via evapotranspiration, or if such consumption is higher or lower than that of native forests, but it is also important to determine whether this increased consumption does not generate water use conflicts (Van Dijk and Keenan, 2007; Lima, 2011). In other words,

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http://dx.doi.org/10.1016/j.foreco.2012.10.015

instead of just trying to determine how much water is used by forest plantations, which is already well studied in numerous conditions, it is also important to evaluate this consumption in relation to the climatic water availability (Calder, 2007). This new approach is based on the catchment water balance and incorporates the concerns of a variety of stakeholders and also includes environmental demands for the maintenance of aquatic ecosystems. Such integration of multiple uses is clearly implied in the multi-dimensional concept of sustainable forest management (Lima, 1998; Nambiar, 1999; Gayoso et al., 2001; Nardelli and Griffith, 2003; Wang, 2004). Thus the socio-ecohydrological analysis of water consumption by forest plantations (Falkenmark and Folk, 2002) serves the fundamental principle of equity of access to water (Nambiar and Brown, 1997; Lima, 2004). The concern over water use by crops and the search for greater water efficiency have intensified due to the expansion of Brazilian plantations to areas with lower water availability. The afforestation of such areas leads to a decrease in catchment stream flow that is lower in absolute terms, when compared to more humid areas, but more severe to local water users (Farley et al., 2005; Scott, 2005).

The role that forest ecosystems play in water conservation, combined with the context of forest plantations that integrates economic (productivity and growth), social (hydrosolidarity and land-use conflicts) and environmental (climate change and biodiversity impacts) factors, generates a pressing question: what forest plantation management strategies can be established to promote water conservation? A fundamental prerequisite for the possible answers to this question is that the catchment forms the basic planning unit. Another important assumption is that the strategies must include at least three scales of analysis: macro, which deals with the analysis of the regional climatic water availability, meso, which is related to the arrangements of the plantations in the landscape, and micro, which deals with the establishment of sustainable forest management practices at the forest management unit (Lima, 2011).

The role of forests in maintaining the quantity, quality and regularity of water flow can be framed within the concept of providing an ecosystem service. This term has been used as a reference for the ecological functions performed by ecosystems and, with respect to forests, relevant ecosystem services would be the support and regulation of the hydrological cycle (Millennium Ecosystem Assessment, 2005).

Forest plantations can provide ecosystem services, but this provision depends on the choice of the management systems (Van Dijk and Keenan, 2007; Scott and Prinsloo, 2008; Vanclay, 2009; Creed et al., 2011). The performance of these plantation areas is usually lower than that of native forests. Nevertheless, forest plantations shows better performance of hydrologic functions than agricultural crops (Van Dijk and Keenan, 2007; Neary et al., 2009; Gordon et al., 2011).

Table 1 shows the theoretical potential of different forest landscapes to provide ecosystem services. The environmental benefits and losses generated by these homogenous monocultures will depend crucially on the forest management plan, which should consider the interaction of forest plantations with other landscape elements in order to contribute to the maintenance of biodiversity and water resources (Cornish and Vertessy, 2001; Creed et al., 2011). Therefore, our focus here will be on different forest plantation ecosystems, using mature native forest as reference, which has the maximum potential performance for all ecosystem services considered, except for evapotranspiration rates that are dependent on its dynamic equilibrium stage (Kuczera, 1987; Vertessy et al., 1996; Scott and Prinsloo, 2008).

Fast growing plantations, such as *Eucalyptus* plantations, are usually managed on short rotations (6–7 years). During this period, they can start to offer some services, such as rainfall interception and soil protection after canopy closure (2–3 years), although at a reduced efficiency when compared with native vegetation (Lima, 1990). Water production and regulation services are generally poorly performed by fast-growing forest plantations, due to the large volumes of water required to reach productivity targets over relatively short timescales, which could reduce catchment water yield and change its flow regime.

The quality of the services provided by forest plantations will depend on the choice of management system used in relation to the regional hydrological availability, and the local physical topographic characteristics. For example, more intensive management systems are typically poor in maintaining hydrologic functions. For this reason the best performance across all hydrologic functions, including water production and the regulation of the stream flow regime, comes from the long-term management of planted forests, less intervention and the possibility of maturation of the forest environment (Hewlett and Hibbert, 1967; Kuczera, 1987; Andréassian, 2004; Brown et al., 2005; Farley et al., 2005; Van Dijk and Keenan, 2007; Calder, 2007; Almeida et al., 2007; Scott and Prinsloo, 2008).

The increased proportion of native forest in the landscape increases the potential for providing ecosystem services, regardless of the dominant land cover type (matrix). Thus, forest plantations interspersed with areas of native vegetation can provide better performance of all ecosystem services. This mosaic of native forest and plantation forests improves the capability of the ecosystem, including water production and regulation of the flow regime, as a result of the lower water demand, greater storage potential and greater buffering effect on riparian areas protected with native forest (Lima et al, 2012a).

In this paper, we show two examples of effective forest management actions based on technical criteria at macro and meso scales that could contribute to improve management systems in order to increase water conservation in forest plantation landscapes. Firstly, at the macroscale, we assess the use of water in different forest plantation areas in Brazil by analyzing the theoretical thresholds for the management of evapotranspiration. Then, we assess effects of different meso-scale forest plantation management alternatives on water flow regulation.

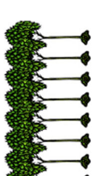
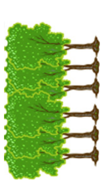
2. Methods

2.1. Precipitation and stream flow data

For the macroscale analysis of evapotranspiration rates, the hydrology data supporting the present analysis were collected from several experimental catchments located in different parts of the country (Fig. 1). These studies were conducted as part of a long-term catchment monitoring and modeling program (PROMAB) carried out by the Institute of Forest Research (IPEF), under the coordination of the Forest Hydrology Laboratory of the Forest Science Department of the University of São Paulo, in partnership with Brazilian forest companies (Lima et al., 2012b). The hydrological monitoring of these catchments involves continuous measurement of precipitation and stream flow. Precipitation is recorded using electronic rain gauges set to record rainfall at a 15-min interval, and discharge using stream gauging stations with different types of weirs, in which water stage is continuously measured by an electronic device, at 15-min intervals. Appropriate equations considering weir dimensions and geometry, were used to calculate discharge at the considered time intervals.

For the meso-scale analysis of water flow regulation, data could only be obtained for one of the experimental catchments (Tinga), which is located in Itatinga, SP (23°02′01″ S; 48°37′30″ W), at the experimental forest station of the University of São Paulo. This catchment covers 68.24 ha and has been planted with *Eucalyptus*

Table 1
Expected ecosystem services provided by different forest cover management systems (+ = very low; ++++ = very high, gray symbols represent performance variation according to management system).

Forest landscape	Potential ecosystem services performance						
	Evapotranspiration	Interception	Soil protection	Riparian services	Water yield production	Flow regulation	Water quality services
Native 	+++	++++	++++	++++	++++	++++	++++
Plantation (fast-wood) 	++++	++++	++++	+	++	+++	+++
Plantation (long term) 	+++	++++	++++	+	++++	++	++++
Plantation (fast) + native 	++++	++++	++	++++	+	+++	+++
Plantation (fast) + native + mosaic 	++	++++	++++	++++	+++	++++	++++

since the 1940s'. During the study period, the Tinga catchment was covered with a 17-year old coppice of a mature *Eucalyptus saligna* plantation (Câmara and Lima, 1999). The analysis includes two monitoring periods: pre-harvest (September 1991 to August 1997) and post-harvest (September 1997 to August 2003). The post-harvest period included the first hydrologic year after harvesting and replacement with a new plantation of the same species.

2.2. Catchment scale evapotranspiration calculation

The precipitation and stream flow data from each of these experimental catchments are usually summarized annually. In order to compute the annual catchment water balance, precipitation and stream flow values are organized for the water year. For most of the catchments, this water year runs from October through September.

Using the water year and considering the average values for the entire monitoring period, the soil water storage is considered negligible, which simplifies the water balance equation to include only the terms: precipitation (P), water yield (Q) and catchment scale evapotranspiration (P–Q). This analysis was used for establishing the relationship between the catchment scale evapotranspiration and annual precipitation (Zhang et al, 2001).

2.3. Annual water yield reduction estimates

For the Tinga catchment (meso-scale analysis), we calculated the annual water yield reduction (QR_t) in relation to the yield observed during the post-harvest period without forest (Q_0), based on following equation:

$$QR_t = \frac{Q_0}{P_0} - \frac{Q_t}{P_t} \quad (1)$$

where QR_t is the annual water yield reduction for year t; Q_0 the yield observed during the post-harvest period without forest (harvest year); P_0 the observed annual precipitation during the harvest year; Q_t the annual yield during year t; P_t the annual precipitation during year t.

Using the observed data, we used non-linear regression to predict the response of annual water yield reduction (QR) over a 25-year period in order to predict it according to forest plantation age (i). Regression analysis and parameter estimation was performed using Sigmaplot software. The age of the plantation was included as a predictor with a log-normal adjustment as follows:

$$QR_t = a \cdot e^{-\frac{1}{2}\left(\frac{\ln\left(\frac{i_t}{x_0}\right)}{b}\right)^2} \quad (2)$$

where t is the year; QR_t the water yield reduction at year t; a, b and x_0 the estimated regression parameters; i_t the forest plantation age at year i (years).

We then used the 25-year annual water yield reduction model to evaluate the impact of different management and landscape composition scenarios on water yield reduction (Table 2).

In the simulated scenarios, we considered that a hypothetic plantation area could be harvested following the forest management plan based on the chosen scenario during a 25-year period. For example, in scenario SE a new forest is established at year 0 covering the total area, and the forest is completely harvested (100%) after 6 years (rotation). For simulation, each partial or total clear-cut was replaced by a new forest plantation with the same characteristics as the old one. When native forest covers part of the landscape, we considered that its rate of yield reduction was similar to that of the 25-year old plantation. Annual yield reduction for each simulated ecosystem was calculated by summing the

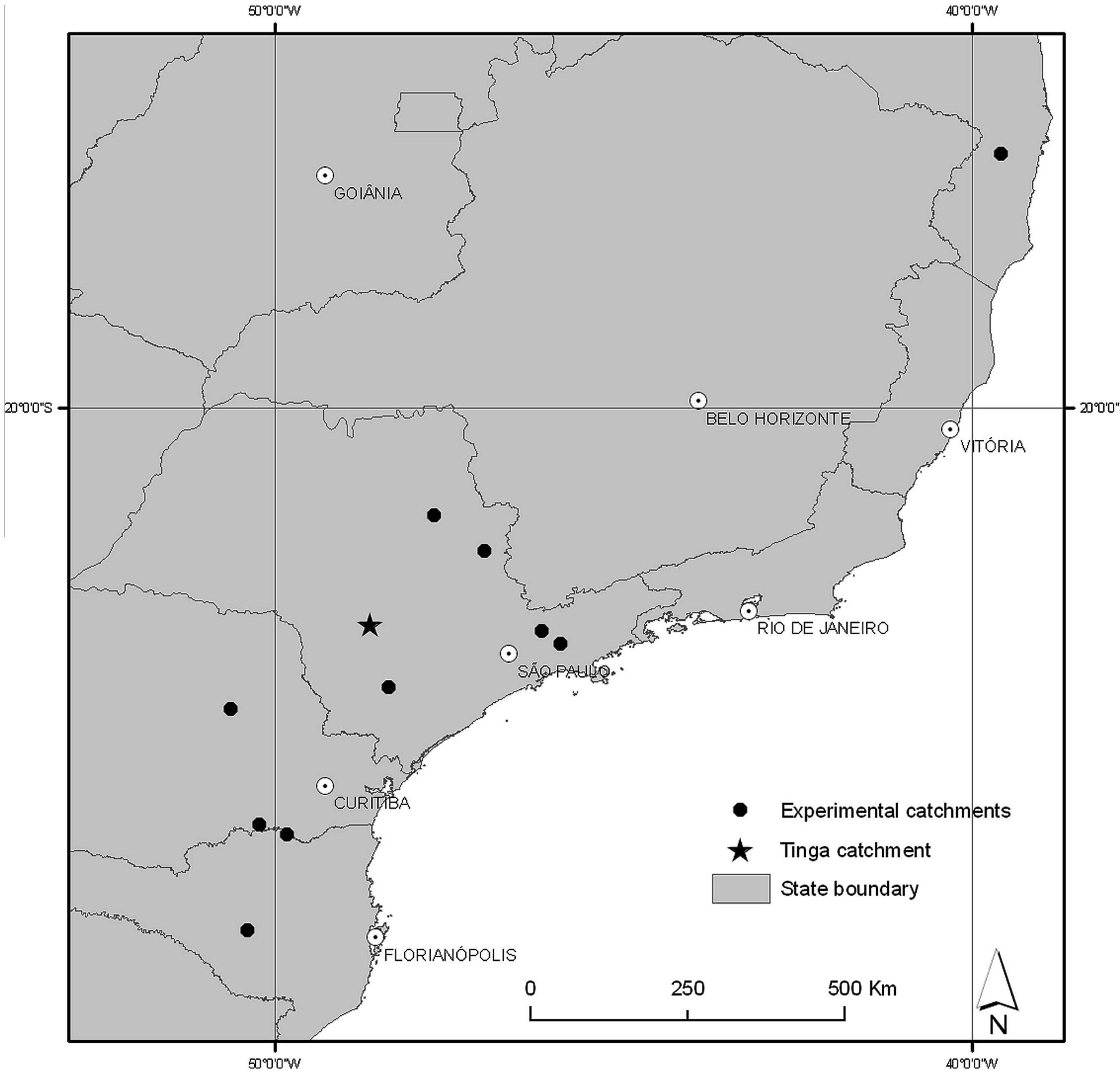


Fig. 1. Location of experimental catchments used for hydrological monitoring of forest plantations in Brazil.

partial effects of yield reduction of proportions of forest at different ages, which were considered as planted in year 0. The total yield reduction for each scenario was therefore calculated as follows:

$$QR_t = \sum_{i=1}^{25} FP_i \cdot QRm_i \tag{3}$$

where t is the simulated year; QR_t the annual water yield reduction for year t (%); i the forest plantation age (years) at year t; FP_i the proportion of the landscape occupied by forest at year t (%); QRm_i the modeled water yield reduction for forest plantation age i (%).

3. Results and discussion

3.1. Catchment scale evapotranspiration

The annual evapotranspiration results from all of the experimental catchments were plotted against annual precipitation (Fig. 2) to enable comparison with the curve obtained by Zhang et al. (2001). This comparison revealed that for the majority of years our data points were above the curve from Zhang, with only a few points below. These points below the curve may be associated with harvest years (with reduced evapotranspiration) and/or years with excessive precipitation. The ratio between ET and P was close to 1, indicating the expected high value of plantation evapotranspiration.

Most of the observations (58%) showed an ET/P ratio greater than 0.90, showing that eucalypt plantations consumed water in proportion to its availability, which is consistent with results from previous studies (Brown et al., 2005; Farley et al., 2005; Almeida et al., 2007). The high proportion of water consumed in relation to that available is probably a reflection of efforts to increase productivity through improved management techniques and the selection of clones with higher water use efficiency, probably derived from the high leaf area of uniform canopies.

Table 2
Summary of forest management scenarios.

Scenario	Rotation length (years)	Native forest proportion (%)	End rotation clear-cut (%)	Annual clear-cut	Description
Short-rotation *Eucalyptus* (SE), no native forest	6	0	100	0%	The management system commonly adopted in Brazil, but here not including areas of native vegetation
Short-rotation *Eucalyptus* + native forest (SEN)	6	30	70	0%	Typical of large areas of certified afforestation in Brazil, with 30% of the landscape occupied by mature native forest
Long-term *Eucalyptus* (LEN) + native forest	15	30	100	1/15	Typical of the long-term management (15 years), adopted for sawmill timber production, with harvesting of 1/15 of the area commencing after 6 years
Short-rotation *Eucalyptus* + native forest + mosaic (SENM)	6	30	70	1/6	Short rotation management, with 30% cover of native forest and management of the area as a mosaic, harvesting 1/6 of the area after 6 years

In regions with high water availability (annual precipitation 1200–1500 mm), approximately 10% of the available water represents an annual water surplus of 120–150 mm, which may be sufficient to maintain water flow in streams for other users and the maintenance of aquatic ecosystems. However, in regions with lower water availability (annual precipitation 800–1000 mm), the surplus may be lower (80–100 mm) and, considering the regional seasonality, this small surplus may be unevenly distributed, resulting in prolonged periods of stream desiccation during the dry season. In some of these regions, such water shortages have generated conflicts over water use between local communities and managers of planted forests (Calder, 2007). Other natural factors related to soil characteristics and topography may also mitigate or aggravate the regional reduction in water flow and must be observed locally.

The scarcity and cost of available land and conflicts with other agricultural activities are shifting forest plantations into marginal areas with lower water availability. This fact, associated with variations in climate and other global changes (Marengo et al., 2010) tends to aggravate these water use conflicts. A multi-scale zoning based on macroscale climatic water balance and regional scale terrain and soil characteristics could assist to make decisions regarding forest plantation expansion (Gush et al., 2002; Calder, 2007; Creed et al., 2011).

Forest growers should take into account the inherent risks of different forest management systems on the regional water availability and consider reducing forest productivity in order to maintain both ecological and social equilibrium, which is necessary for the long term sustainability of the plantation operations. Also, it is essential to maintain catchment scale monitoring programs (Almeida et al., 2007; Lima, 2011), with the paired catchment approach in which the control catchment is covered with native forest, in order to understand forest plantation effects on stream flow and catchment water balance.

Thus, monitoring of regional water availability and its distribution throughout the year is necessary, so that mitigation measures can be implemented at other scales (meso and micro), to prevent further social and environmental damage. For example, at the meso-scale, land use planning is essential and must include reserves of native habitat, creation of mosaics, increased rotation length and management for multiple uses. At the micro scale of the forest management unit, decisions on alternative spacing, species or clones may contribute to reduce water consumption.

3.2. Water yield reduction

Table 3 presents the observed values of precipitation, water yield, Q/P and yield reduction for each plantation age studied at the Tinga catchment, in Itatinga, São Paulo. In older plantations (12–17 years) the Q/P ranged between 0.206 and 0.425, with an average yield reduction of approximately 15%. At the beginning of the new planting (greater than 1 year), Q/P was between 0.189 and 0.337, with a reduction in water yield of about 25%.

The log-normal model fitted the observed data well (R^2 = 0.7391). The model fitted almost perfectly the observed data up to a plantation age of 5 years (Fig. 3). The data between 12 and 17 years were highly variable. Nevertheless, the model curve gives us the probable magnitude of yield reduction with stand age. From 17 years, the model predictions could not be validated due to a lack of observed data beyond this age. The expression obtained by the fitted model was:

$$QR_t = 0.2794 \cdot e^{-\frac{1}{2}}\left(\frac{ln\left(\frac{i_t}{5.5815}\right)}{0.8326}\right) \qquad (4)$$

where QR_t is the water yield reduction at year t; and i is the forest plantation age at year t (years).Previous studies have also found the same trend of yield reduction in native *Eucalyptus regnans* forests (Kuczera (1987), Vertessy et al. 2001) and with other native *Eucalyptus* species (Lane and Mackay, 2000). It is interesting to point out that our model is the first, outside of Australia, to indicate a decrease in yield reduction as the *Eucalyptus* stand ages. In the conditions of the present study, *Eucalyptus* would reach maturity between 25 and 30 years old, when the model curve stabilizes. The model represents a forest plantation without management operations, which is different from conventional long term forest management aimed at sawmill production, which are normally submitted to thinning, altering the forest structure and modifying the pattern of water consumption with plantation age. The highest water yield reduction occurred between 3 and 7 years, which corresponds to the fastest growing period for tropical *Eucalyptus*, when it probably has the highest Leaf Area Index (LAI).

Fig. 4 shows results obtained from modeling the different forest management scenarios. The SE scenario represents the management system where 100% of the area is managed for plantation. This scenario does not include areas of native vegetation (Fig. 4A) and could represent the maximum land-use intensity. This scenario is not common in Brazil due to environmental laws which require the preservation of native vegetation at the property level. Our model showed that the effect on yield increased during the rotation period, reaching 28%, but without stabilizing at the time of harvest (6 years). After harvesting, the effect appeared to be nullified, but increased again during the subsequent rotation. The model of this scenario showed that there was great variation in the yield during rotation periods, alternating between periods with a high yield reduction and periods with little or no effect, as observed by Câmara and Lima (1999).

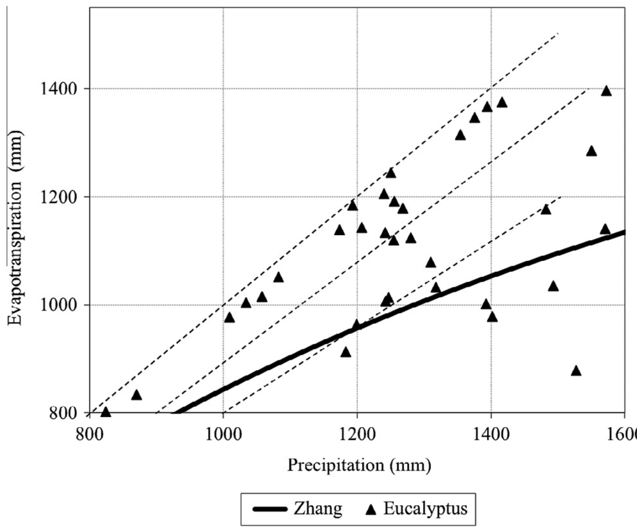


Fig. 2. Annual catchment scale precipitation and evapotranspiration observed at forest plantation sites in Brazil (Lima et al., 2012b).

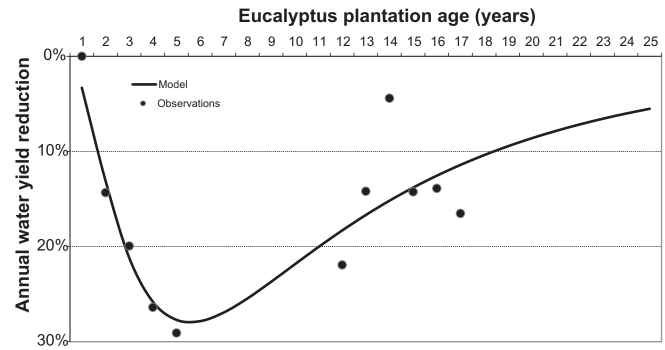


Fig. 3. Log-normal model of the observed yield reductions at different eucalypt plantation ages in the Tinga stream catchment, EECF Itatinga.

Table 3
Observed values for precipitation (P), water yield (Q), quotient Q/P and water yield reduction for different plantation ages, in the Tinga stream catchment.

Hydrological year	Forest age (years)	Rotation	P (mm)	Q (mm)	Q/P	Water yield reduction ($Q_0/P_0 - Q/P$) (%)
91–92	12	5th (coppice)	1482.4	305.3	0.206	22
92–93	13	5th (coppice)	1959.9	593.2	0.303	14
93–94	14	5th (coppice)	1527.6	649.1	0.425	4
94–95	15	5th (coppice)	1402.0	423.3	0.302	14
95–96	16	5th (coppice)	1493.0	457.6	0.306	14
96–97	17	5th (coppice)	1570.9	429.7	0.274	17
97–98	0	1st	1967.4	929.5	0.472	–
98–99	1	1st	1333.2	634.8	0.476	0
99–00	2	1st	1141.4	384.3	0.337	14
00–01	3	1st	1392.3	390.8	0.281	20
01–02	4	1st	1317.5	284.8	0.216	26
02–03	5	1st	1242.5	235.1	0.189	29

The SEN scenario (Fig. 4B), a scenario typical of large areas of certified afforestation in Brazil, showed a similar pattern to that observed in the SE scenario. Including native vegetation (in this scenario considered as mature and stable native forest) did however appear to mitigate impacts of the SE scenario. In the SEN scenario, the presence of native vegetation reduced the yield variation during plantation growth and the maximum rainy season flow was also reduced by approximately 20%. The same effect was observed by Van Dijk and Keenan (2007) and Lima et al. (2012a).

Comparing SE and SEN scenarios, it was possible to observe the effect of Brazilian environmental law on forest plantation landscapes, with the SEN scenario reducing the flow variation and water use by plantations. Considering this, we could say that the mosaic of forest plantations and native vegetation observed in most certified areas in Brazil could represent a management strategy where impacts of forest plantation on water are reduced by the preservation of native vegetation at the landscape scale. This new landscape-based approach is different from the conventional fast-growing plantation monoculture, as the inclusion of 30–40% of native vegetation is responsible for a more hydrologically stable landscape, which is in line with FAO recommendations related to the adoption of management strategies aimed at transforming plantations into forests (FAO, 1991).

The LEN scenario (Fig. 4C) represents the typical long-term (15 year) management system adopted for sawmill timber production and included the maintenance of native vegetation and a gradual clear cutting after the first 15 years. This was the most conservative scenario, with gradual timber harvesting resulting in a large reduction in water yield during the early stages of forest growth, which was mitigated during the maturation of the forest and balanced with the annual harvests, stabilizing the reduction in yield at approximately 14%. This scenario shows a pattern also observed by other studies (Kuczera, 1987; Scott and Smith, 1997; Almeida et al., 2007; Rodríguez-Suárez et al., 2011).

The SENM scenario (Fig. 4D) represents a situation found in some partially reforested areas, which manage various species for different purposes. However, this scenario is uncommon in industrial *Eucalyptus* plantations. This scenario showed the combined effects of the maintenance of native vegetation, with partial harvests within a forest mosaic system. The yield reduction curve for this scenario showed a pattern very similar to the LEN scenario, with an initial reduction in yield and stabilization at approximately 15% after 10 years.

The modeled scenarios have limitations, because they include only additive effects of the reduction of yield in each landscape patch occupied by plantations of different ages. However, there are likely to be interactions between the different forest covers that we did not consider, which could increase or decrease water consumption. Considering the difficulty of long-term monitoring, the 17 years of data presented provide an important advance in the understanding of the behavior of water yield during the maturation of plantations; however, more robust process- based models may be used to generate improved simulation scenarios.

The water yield patterns differed substantially between scenarios and in relation to the mean yield (460 mm) observed during the monitoring period (Fig. 5). There was a large yield variation in the SE scenario, with an average value of 400 mm. Although there was also considerable yield variation in the SEN scenario, this was less than the SE scenario, which also had a greater mean yield (410 mm). The LEN scenario had much less yield variability compared with the SE and SEN scenarios, with a mean value of approximately 390 mm, with a few extreme values observed at the beginning of the period followed by stabilization. The SENM scenario showed the lowest variability, and quickly stabilized at a value of 388 mm.

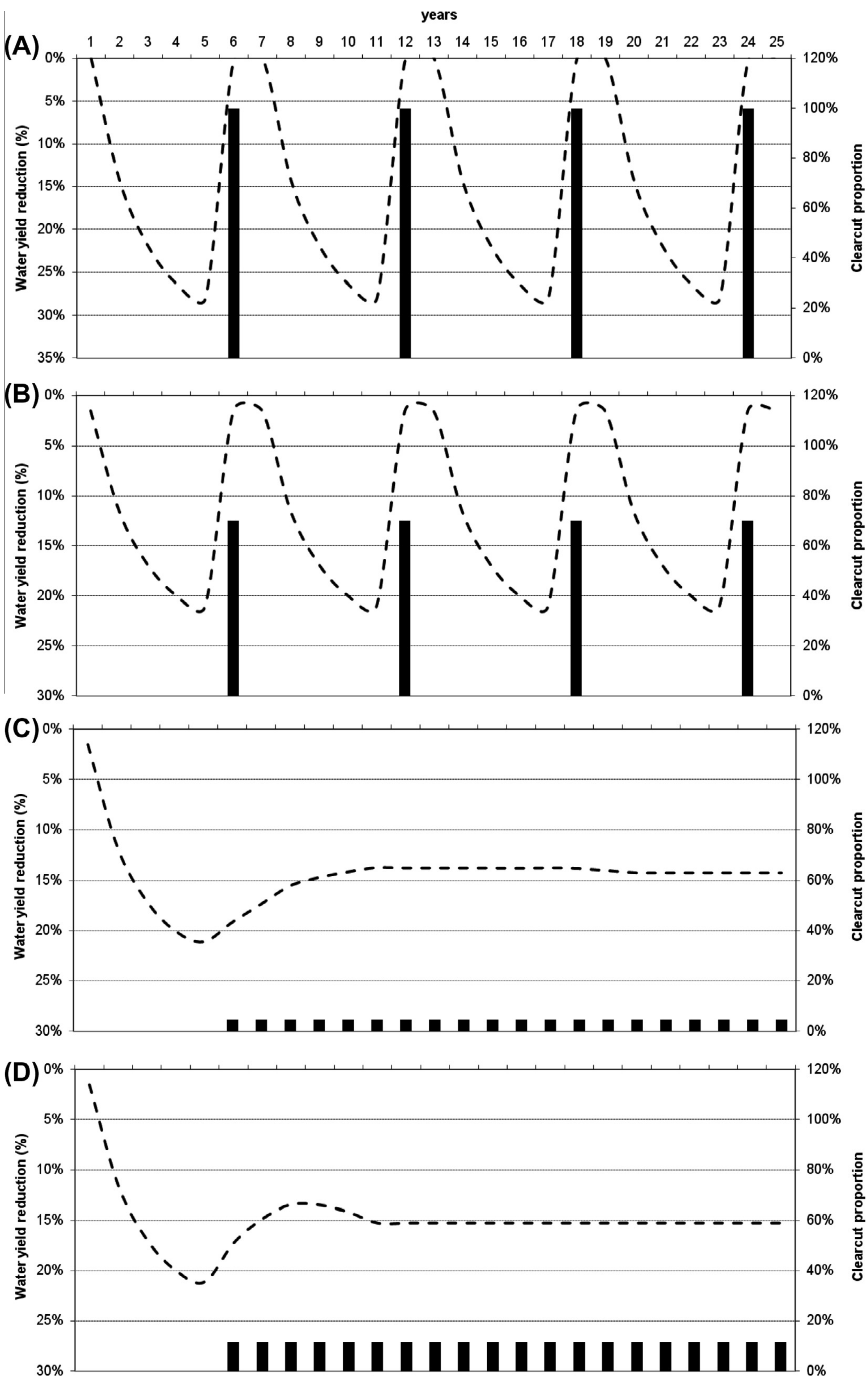


Fig. 4. Yield reduction (%) during 25 years of different eucalypt plantation management scenarios: (A) Fast growth *Eucalyptus* (SE); (B) Fast growth *Eucalyptus* with maintenance of 30% native vegetation cover (SEN); (C) Long term management of *Eucalyptus*, with maintenance of 30% native vegetation cover (LEN); and (D) Fast growth *Eucalyptus*, with maintenance of 30% native vegetation and a mosaic management system (SENM).

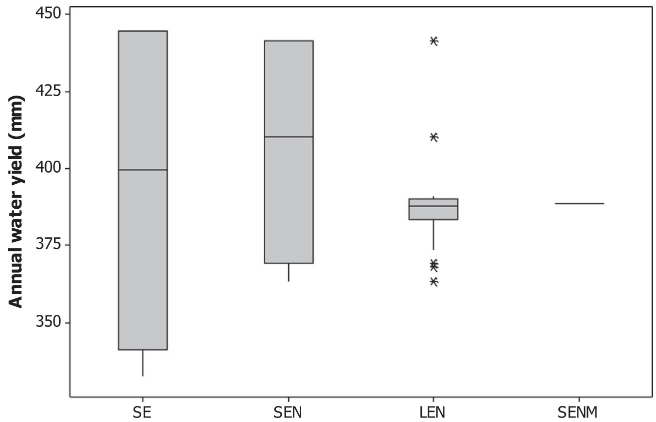


Fig. 5. Box plot of estimated annual water yield for the Tinga stream catchment, under different management scenarios: (A) Fast growth *Eucalyptus* (SE); (B) Fast growth *Eucalyptus* with maintenance of 30% native vegetation cover (SEN); (C) Long term management of *Eucalyptus*, with maintenance of 30% native vegetation cover (LEN); and (D) Fast growth *Eucalyptus*, with maintenance of 30% native vegetation and a mosaic management system (SENM).

The lowest average water use was found in the LEN scenario, which was expected based on the decline in growth found in this type of forest stand after the harvesting period. However, the average consumption may increase if the forest is managed with thinning, as the understory growth associated with this management practice may also consume water (Whitehead and Kelliher, 1991).

4. Conclusions

Our study shows examples of opportunities for increasing water conservation in forest plantation landscapes, improving fast-growing plantation management via strategies that meet both forest productivity and water conservation goals. Our results suggest that the development of management strategies across at least three scales is necessary for effective water conservation in *Eucalyptus* plantations. The first scale to be considered involves the natural climatic constraints of water availability in different regions. At this scale, evidence shows that forest plantations in the tropics use water according to availability, which indicates that water availability zoning and the choice of more water efficient species/varieties and forest management options are crucial for water conservation.

Secondly, at the meso-scale, management should consider the maintenance and provision of environmental services across the landscape, specifically water quantity and flow regulation, which are necessary for the conservation of biodiversity, riparian ecosystems and social values. At this scale, we found that the proportion of native forest in the landscape plays an important role in the reduction and regulation of water use, and therefore mosaic management could stabilize flows from plantation areas. Finally, at the operational micro scale of the forest management unit, the establishment of the catchment as the planning unit is a fundamental management strategy necessary for incorporating water conservation into the forest management plan.

Acknowledgements

Most of the results in this paper are based on work conducted as part of the Cooperative Research Program between IPEF and Brazilian Forest Companies (PROMAB). We are grateful to numerous assistants and employees of the participating companies for their valuable cooperation.

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