

HISTORICAL LAND-COVER/USE IN DIFFERENT SLOPE AND RIPARIAN BUFFER ZONES IN WATERSHEDS OF THE STATE OF SÃO PAULO, BRAZIL

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ABSTRACT: Information about the land cover of a region is a key information for several purposes. This paper aimed to elaborate land-cover maps using digital satellite images obtained in 1997 from seven watersheds (Piracicaba, Moji-Guaçu, Alto Paranapanema, Turvo Aguapeí, Peixe, and São José dos Dourados) located in the State of São Paulo, southeastern Brazil. Additionally, this study evaluated the relationship between land-cover and slopes of the terrain of the seven watersheds. A third objective was to estimate the percentage of riparian vegetation currently remaining along the streams in a 30-meter width buffer zone. Three research questions were posed: *i*) What is the dominant land-cover of these watersheds? *ii*) Is the riparian vegetation well preserved in the 30m width buffer zone? If not, *iii*) what is the dominant land-cover in these areas and what would be the cost of recovering such areas? Pasture was the predominant land-cover, occurring in approximately 50% of the entire study area, while sugar cane (*Saccharum officinarum*) (14%) constituted the second most frequent land-cover. Approximately 50% of the area of the seven basins is considered flat (40%) or smoothly rolling (10%). The terrain only becomes hillier in the Piracicaba and Alto Paranapanema basins, where a little less than 50% have slopes higher than 8%. The total riparian buffer strip zone occupied an area equivalent to approximately 6,200 km². From this total, only 25% is preserved. Pasture is the main land-cover of the riparian buffer strip zone.

Key words: land planning, land management, geoprocessing, catchments, rivers

COBERTURA VEGETAL EM DIFERENTES USOS DO SOLO E DECLIVIDADES DO TERRENO EM BACIAS HIDROGRÁFICAS DO ESTADO DE SÃO PAULO, BRASIL

RESUMO: Informações sobre mudanças no uso e cobertura do solo são fundamentais para vários propósitos sociais, econômicos e ambientais. O principal objetivo deste estudo foi elaborar mapas de cobertura do solo usando imagens digitais obtidas por satélite no ano de 1997 nas seguintes bacias hidrográficas do Estado de São Paulo: Piracicaba, Moji-Guaçu, Alto Paranapanema, Turvo Aguapeí, Peixe, and São José dos Dourados. Adicionalmente, a relação entre a cobertura do solo e a declividade do terreno também foram investigadas. Um segundo objetivo foi estimar a proporção relativa de vegetação ripária considerando-se uma faixa de 30 metros em relação às margens dos corpos d'água. As três principais questões científicas deste artigo foram: *i*) Qual é a cobertura dominante do solo nas bacias hidrográficas abordadas? *ii*) As vegetações ripárias encontram-se bem preservadas ripária nas faixas dos 30 metros? Em caso negativo, *iii*) Qual é a cobertura do solo dominante nessas áreas? A cobertura do solo predominante nas bacias hidrográficas são as pastagens, ocorrendo em quase 50% de toda a área investigada. Seguem-se as plantações de cana-de-açúcar (14%) como sendo as coberturas do solo mais importantes. Aproximadamente metade da área das sete bacias foi considerada plana (40%) ou suavemente ondulada (10%). A área ripária considerando-se uma largura de 30 metros em relação às margens dos corpos d'água ocupa uma área aproximada de 6.200 km². Deste total, somente 25% encontram-se bem preservadas. Dentre as culturas, as pastagens ocupam a maior área na zona ripária. Nas bacias dos rios Moji-Guaçu e Piracicaba a cana-de-açúcar é a principal cultura invasora da zona ripária.

Palavras-chave: planejamento espacial, manejo de bacias, geoprocessamento, rios, redes de drenagem

INTRODUCTION

Through multiple land-use changes, biological systems support human needs regarding food, fiber and energy (Vitousek et al., 1997). Therefore, land-use changes are crucial to human well-being (Lambin et al., 2003). On the other hand, land-use changes often alter the structure and functioning of ecosystems by modifying the composition of plant and animal communities as well as nutrients, water cycles, and local climate (Webb et al., 2005; 2006; Lambin et al., 2003; Daniel et al., 2002; Mander et al., 2000; Ojima et al., 1994, Houghton, 1994). In addition, several studies show that land use indices are strong predictors of river water quality (e.g. Ometto et al., 2000). Therefore, information on how land-cover is historically altered is essential for improved management of aquatic and terrestrial resources of a watershed.

The State of São Paulo, located in southeastern Brazil, is the most industrialized and populated region of Brazil, being responsible for 40% of the gross domestic product of the country. Some regions of the State of São Paulo face the same problems as other over populated and industrialized areas of the developing world: increasing deterioration of water resources coupled to decreased water availability (Martinelli et al., 2002; Groppo et al., 2006). In order to meet such challenges, at the beginning of the Nineties, the State was divided in twenty-one hydrologic units corresponding to one or more meso scale watersheds, decentralizing the water management of the State. Consequently, it is fundamental that a body of environmental, social and economic information be readily available to water managers of these watersheds. Currently, this detailed information on land-cover and land use of watersheds is lacking.

Based on this lack of information, the first objective of this paper was to describe the land-cover and land use in 1997 of seven meso scale watersheds located in the State of São Paulo and to investigate the relationships between the land-cover and the slopes of the terrains of the study area at the time. Since the area of remaining original forests is already mapped, the second objective of this study was to estimate the percentage of riparian vegetation currently remaining along the streams of the seven basins of this study in a 30 m-width buffer zone.

This study considers: *i*) what is the dominant land-cover of these watersheds? *ii*) is the riparian vegetation well preserved in the 30 m-width buffer zone? If not, *iii*) what is the dominant land-cover in these areas and what it cost to recover such areas?

MATERIAL AND METHODS

Study area

The land-cover of seven watersheds located in the State of São Paulo, southeastern Brazil was mapped. They comprise 36% of the area of the State of São Paulo (Figure 1), which is the most industrialized and populated state of the country. In 2002, 22% of the Brazilian population lives in the State of São Paulo, which is responsible for 40% of the Brazilian Gross Domestic Product (IBGE, 2002). The land uses of the following watersheds were mapped: Piracicaba, Moji-Guaçu, Alto Paranapanema, Turvo Aguapeí, Peixe, and São José dos Dourados. Most of these watersheds are located entirely in the State of São Paulo. Exceptions are the Moji-Guaçu and the Piracicaba watersheds, of which approximately 10% is located in the State of Minas Gerais. These were selected due to their economic importance, as well as their importance as under-surveyed areas in relation to aquatic biodiversity.

The area of the basins varied from 5,800 km² (São José dos Dourados) to 22,804 km² (Alto Paranapanema). In addition to these extremes, the size of the basins varied from approximately 11,000 to 22,000 km² (Table 1). The average annual rainfall is similar in all of them, varying from a minimum of 1,220 mm per year in the Aguapeí basin up to a maximum of 1,460 mm per year in the Moji-Guaçu basin (Table 1). The smallest average discharge was observed for the São José dos Dourados River (52 m³ s⁻¹) and the largest for the Paranapanema River (310 m³ s⁻¹) (Table 1). The most populated basin is by far Piracicaba, with almost 4 million people, followed by the Moji-Guaçu basin with 1.3 million people (Table 1). All other basins have less than 1 million people, notably the São José dos Dourados basin that has only 210,000 inhabitants (Table 1). The population density in the Piracicaba basin was also the largest: from 3 to 5 times larger than

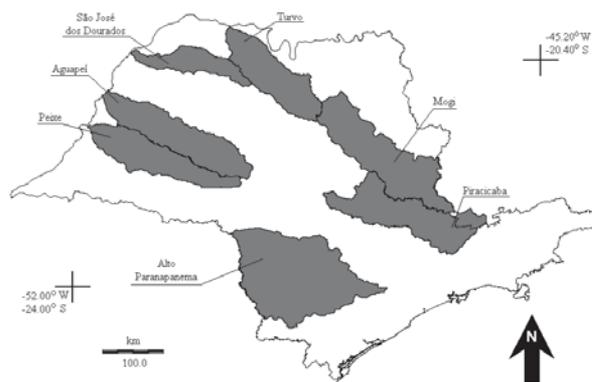


Figure 1 - Map of the São Paulo state showing the seven studied basins in dark grey contours.

Table 1 - Basic characteristics of the seven watersheds investigated in this study. Source: São Paulo (1990). SJD - São José dos Dourados, AGUA - Aguapeí, PEI - Peixe, TUR - Turvo, ALPA - Alto Paranapanema, MOG - Moji-Guaçu, PIRA - Piracicaba.

	SJD	AGUA	PEI	TUR	ALPA	MOG	PIRA
Area (km ²)	5,800	12,240	12,980	11,500	22,804	13,310	12,500
Average annual rainfall (mm)	1,250	1,220	1,250	1,250	1,290	1,460	1,405
Average discharge (m ³ s ⁻¹)	52	97	112	122	310	194	141
Population (x 10 ⁶)	0.21	0.59	0.79	0.87	0.68	1.3	3.4
Population density (inhab./km ²)	61	74	110	84	34	96	341
Rate of urbanization (%)	85	89	92	92	75	91	95
Water use - industrial (%)	7.6	14.8	12.2		15.4		40.7
Water use - urban (%)	9.8	13.4	22.2		4.0		35.6
Water use - irrigation (%)	82.6	71.8	65.6		80.6		18.6

those of other basins, where the population density varied from 34 to 110 inhabitants per km² (Table 1). Most of the population is concentrated in urban centers; as a consequence, the urbanization rates are higher than 80-90%, with the exception of the Alto Paranapanema basin, where the rate is only 75% (Table 1).

Finally, the water use for the Turvo and the Moji-Guaçu basins is unavailable. In most of the other basins, water is mainly used for irrigation (Table 1). An exception was in the Piracicaba basin, where water is mainly used by industries, followed by population (Table 1).

Land-cover and Land Use Maps

The satellite scenes of the river basins for the years 1996 and 1997 were obtained from "Instituto Nacional de Pesquisas Espaciais" (INPE), in São Paulo, Brazil. The drawings were previously georeferenced as well as atmospherically, and radiometrically corrected. All images were projected in a common system (Universal Transverse Mercator, Datum Córrego Alegre). Land use and land-cover maps of the study areas were generated through digital classification (digital supervised classification) of eleven TM-Landsat5 images (path-row: 221/74 (acquired in August 31, 1996) (with these dates, consider an abbreviated style: (8/31/96); 222/74 (August 6, 1996); 219/75 (August 17, 1996); 220/75 (August 24, 1996); 221/75 (July 30, 1996); 222/75 (September 7, 1996); 223/75 (July 15, 1997); 220/76 (August 24, 1996); 221/76 (April 25, 1996); 220/77 (April 18, 1996); and 221/77 (September 7, 1996) - color compositions - bands TM3, TM4, and TM5), using the maximum likelihood method (Lillesand & Kiefer, 2000). The classification step was performed using the "Makesig" and "Maxlike" commands of the IDRISI software (Eastman, 2001).

The classification accuracy was checked through a field survey. In June 2002, we visited 230

randomly selected points. In this visit, the land-cover around these points (in a radius of approximately 250 meters) was recorded, and the geographic coordinates were checked with a GPS receiver. The Kappa index of agreement was calculated using the "Errmat" command of the Idrisi (Eastman, 2001). The overall accuracy of the classification was 90% and the Kappa index of agreement was 0.85.

The land-cover in the map legends are: pasture, remnant forest, urban, perennial crops, annual crops, water bodies, bare soil, reforestation, sugar cane, and a general class called "other". The land-cover classification was conducted for all watersheds, except for the Piracicaba. For this specific watershed, the land-cover map, which is already available, can be found at: www.cena.usp.br/piracena. This land-cover map (referring to land-cover situation of the region in 1997) was converted to a format equal to the other, and the step to generate the land use maps and date was also computed for this watershed. The land use maps were created by reclassification (command "Reclass" of the Idrisi) based on the land-cover maps. Pasture, perennial crops, annual crops, sugar cane, bare soil, and reforestation were reclassified into one class: "agrosilvipasture". The class "remnant forest" was reclassified as "conservation - relics", the class "urban" was reclassified as "urbanization", and finally the classes water bodies and "other" were classified as "water-bodies/other".

Digital Terrain Models and Slope Maps

The Digital Terrain Models (DEM) were purchased from Imagem Sensoriamento Remoto (www.img.com.br) for almost all watersheds, except the DEM for the Piracicaba River basin which was acquired from the Piracena project database (www.cena.usp.br/piracena/). All of these DEMs have a 20 m spatial resolution. The slope maps were gen-

erated by the Slope command of Idrisi (Eastman, 2001). After the generation of the slope maps for all watersheds, they were converted into a 30m spatial resolution throughout the command “resample” of the Idrisi, to permit cross-tabulation among the slope maps and land-cover maps. Before the cross-tabulation, the slope maps were reclassified into four slope categories (Santos et al., 2005): flat (<3%); smoothly rolling (3 to 8%); rolling (8 to 20%); and hilly (>20%). The slope and land-cover maps were cross-tabulated to generate thematic information showing the land-cover class according to slope class.

Riparian buffer zone

The development and analysis of riparian buffer zones required the implementation of several preliminary steps. First, a contemporary 1:50,000-land-cover map was generated from a Landsat TM scene. Second, stream network data (vector format) were extracted from the satellite images through the on-screen digitalization procedure. Third, the dimension of the buffer zone was determined according to the Brazilian Forest Code (www.ipef.br) and type of material available. Fourth, the buffer zones were defined using the stream network through the “Buffer” routine of the Idrisi 32 software (Eastman, 2001). Fifth, the maps containing the buffer zones and the land-cover were overlaid (“Overlay” routine of the Idrisi, with the option multiplication) in order to generate a new map containing the land-cover of the buffer zones. Finally, the areas of each land-cover class were calculated (“Area” routine of the Idrisi).

Additionally, the cost of the complete riparian vegetation restoration program was calculated for the detected areas with no riparian vegetation. The cost of the restoration per hectare was provided by Dr. Ricardo Ribeiro Rodrigues (Biological Sciences Department, Escola Superior de Agricultura “Luiz de Queiroz”, University of São Paulo). The total cost of restoration is approximately R\$ 7000/ha, which is equivalent to approximately U\$ 3350/ha (dollar to real ratio 2.0885; February 23, 2007), and involves three main phases. The implementation phase, which is the most extensive, equivalent to 75% of the total cost of the project, and a first and a second year of maintenance, equivalent to 15% and 10% of the total cost of the project, respectively. The most costly restoration item is labor, which accounts for almost 47% of the cost. The cost involved in applying pesticides and fertilizers, including machinery used in these operations, is 36% of the total cost. Finally, the cost of seedlings is only 12% of the total cost.

This estimate is a preliminary step in estimating the cost of restoration of riparian areas. It involves

several assumptions such as extrapolating the budget shown above to the entire State of São Paulo, which may not be accurate. Additionally, our estimates do not account for economies of scale, which may accrue when large areas are reforested.

In 1999, the Brazilian Forest Legislation established that the riparian vegetation must be preserved in a: *i*) 30m width of each margin for streams up to 10 m width; *ii*) 50 m width of each margin for streams from 10 to 50 m width; *iii*) 100 m width for rivers from 50 to 200 m width; *iv*) 200 m width for rivers from 200 to 500 m width; and *v*) 500 m for rivers higher than 600 m width (www.ipef.br). In order to facilitate our estimates, we adopted a buffer width of 30m of each margin independent the river width. Therefore, our estimate is the minimum width required by law, which under estimates the area needing to be preserved.

RESULTS AND DISCUSSION

Land-cover and Land Use Maps

An area approximately equivalent to 88,300 km² was mapped in this study, corresponding to almost 36% of the entire area of the State of São Paulo. Pasture is the main land-cover (approximately 50%) of the entire mapped area (Table 2). It is not the main land-cover only in the Moji-Guaçu basin, and in the central part of the Piracicaba basin (Figure 2). On the other hand, in some watersheds, such as the São José dos Dourados, the Aguapeí, and the Peixe, pasture is by far the main land use (Figure 2).

Sugar cane, one of the most cultivated and economically important crops in the State of São Paulo, covers approximately 14% of the study area. The Moji-Guaçu basin has the greatest area covered by sugar cane (39%), and the Piracicaba basin has the second greatest area (34%) (Table 2). This crop covers most parts of the Moji-Guaçu basin, while in the



Figure 2 - Spatial distribution of pasture in seven basins of the State of São Paulo.

Table 2 - Land-cover classes and their respective areas (km²) and proportions.

Land-cover class	ALPA		TUR		AGP		PEI		SJD		PIRA		MOG		SUM	
	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%
Pasture	10,826	48	6,046	61	8,972	74	6,871	68	4,117	78	5,466	43	3,011	20	45,308	51
Natural forest	5,959	26	1,553	16	1,541	13	1,545	15	364	7	1,276	10	14,812	10	13,720	16
Sugar cane	144	0.6	668	7	479	4	343	3	110	2	4,258	34	5990	39	119,938	14
Bare soils	594	3	893	9	251	2	274	3	367	7	34	0.3	3312	22	5,722	6
Reforest.	2,442	11	9	0.1	18	0.2	10	0.1	1	0.1	528	4	663	4	3,672	4
Perennial crops	1,053	5	448	5	518	4	969	10	171	3	17	0.1	228	1	3,403	4

ALPA - Alto Paranapanema; TUR – Turvo; AGP – Aguapeí; PEI – Peixe; SJD – São José dos Dourados; PIRA – Piracicaba; MOG – Moji-Guaçu; SUM – summation

Piracicaba basin, sugar cane is more concentrated in the western portion of the basin (Figure 3), where the topography is gentler than in the eastern portion of the basin (www.cena.usp.br/piracena). In other watersheds, such as the Alto Paranapanema, sugar cane occupies less than 1% of the area and is clustered in the final portion of the basin (Table 2). The bare soil occupied approximately 7% of the mapped area and is associated to sugar cane in two periods: (i) immediately after harvesting or (ii) immediately before replanting the crop (Table 2).

The remnant of natural vegetation corresponds to 15.5% of the entire study area. This class of land-cover includes patches of the Atlantic Forest biome, such as the Ombrophyllus Dense Forest, and the Semi Deciduous Mesophytic Forest, and several physiognomies of the Cerrado, a tropical savanna-like vegetation. The Alto Paranapanema has the highest area covered with natural vegetation (26%), which is mainly concentrated in the southern portion of this basin (Figure 4), while in São José dos Dourados only 7% of the area is covered with natural vegetation (Table 2).

Reforestation is composed of *Eucalyptus* sp. and *Pinus* sp. species farms (Kronka, 2002). Both occupy an area equivalent to 4% of the entire area, which

is a little lower than the average value for the entire State of São Paulo (5%) (IEA web site, see references). Reforestation is important mainly in the Alto Paranapanema (11%), the Moji-Guaçu (4%), and the Piracicaba basins (4%). In the remaining watersheds, reforestation occupies less than 1% of the area (Table 2 and Figure 5).

The perennial crops cover approximately 4% of the entire mapped area (Table 2). Perennial crops are especially important in the watersheds located in



Figure 3 - Spatial distribution of sugar cane in seven river basins of the State of São Paulo.



Figure 4 - Spatial distribution of original vegetation in seven river basins of the State of São Paulo.



Figure 5 - Spatial distribution of reforestation in seven watersheds of the State of São Paulo.

the western portion of the State of São Paulo (Figure 6), especially in Peixe, where almost 10% of the area is covered by perennial crops. During field visits it was noticed that the main perennial crops were: citrus, coffee, and rubber trees. Coffee was the main crop in the Aguapei and Peixe watersheds, near the city of Marília, and also in the steep slopes located in the headwaters of the Moji-Guaçu basin. Citrus orchards were more common in the Turvo (near the city of São José do Rio Preto) and in the central part of the Moji-Guaçu watersheds. Finally, rubber tree farms were also common in the Turvo, as well as in the São José dos Dourados watersheds.

Annual crops occupy only 2% of the mapped area, and are mainly represented by corn (*Zea mays*), wheat (*Triticum sp.*), and soybean (*Glycine max*). Other annual crops such as cotton (*Gossypium sp.*), zucchini (*Curcubita sp.*), and beans (*Phaseolus sp.*) were also observed, but in small proportion as compared to the first three crops. During the field visit, it was observed that corn is spread along several watersheds, while wheat and bean fields are mostly concentrated on the Alto Paranapanema watershed, which had the highest proportion of this type of land-cover (4%), while Peixe had the smallest proportion (0.13%).

Urban centers comprise approximately 2% of the entire study area. The watershed with the highest percentage of urbanization is Piracicaba (6%) due to a significant number of densely-populated cities such as Campinas, Rio Claro, Americana, Piracicaba, and Limeira. These cities are all located in the central part of the basin, and form a continuous urbanized area from Campinas to Piracicaba (Figure 7). The Piracicaba watershed is followed by Moji-Guaçu and Turvo that have almost 2% of urbanized area (Table 2). The basin that presents the smallest percentage of urban centers was Alto Paranapanema (0.4%).



Figure 6 - Spatial distribution of perennial crops in seven watersheds of the State of São Paulo.

The water bodies comprise 1.3% of the study area. The watershed with the largest body of water is Alto Paranapanema with the Jurumirim reservoir, a dam built on the Paranapanema River in the late 1960s. The Piracicaba basin has the second highest percentage of area covered by water, mainly due to the Barra Bonita reservoir. The class “other” is represented by patches that were not identified by the classifier and represents 0.3% of the study area. The Moji-Guaçu watershed presents the highest value for this land-cover class, perhaps due to the natural complexity of land-cover along this basin.

Slope classes and land use

Approximately 40% of the area of the seven watersheds fall in a slope class considered as flat (<3%) (Figure 8). If the next slope class is considered (3-8%, smoothly rolling), more than 50% of all basins are either flat or smoothly rolling. This is especially true in the watersheds of western São Paulo State



Figure 7 - Spatial distribution of urban settlements in seven watersheds of the State of São Paulo.

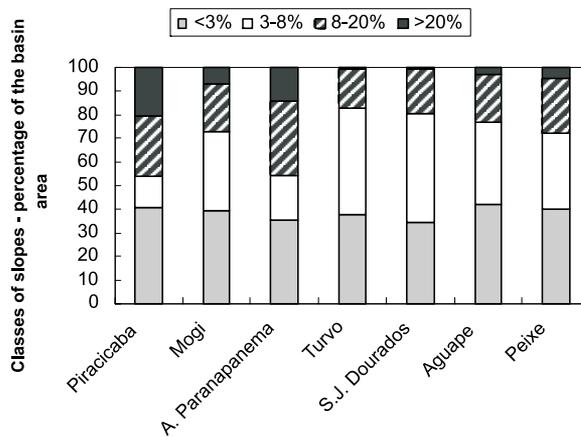


Figure 8 - Percentage area of each basin under different classes of slopes: flat (<3%); smoothly rolling (3-8%); rolling (8-20%) and hilly (>20%).

– Turvo, São José dos Dourados, Aguapeí, and Peixe – where more than 70% of the area of these basins have slopes <8% (Figure 8). The terrain only becomes hillier in Piracicaba and Alto Paranapanema, where a little less than 50% of the area has slopes higher than 8% (Figure 8).

Pasture is the main land-cover of the watersheds occurring in most slope classes, especially in Piracicaba, Moji-Guaçu, and Turvo, where pasture is also present on higher slopes (Figure 9). Sugar cane occupies mainly the flat areas of the terrain in the Moji-Guaçu and Piracicaba watersheds (Figure 9). Finally, the remaining original vegetation occurs in different slope classes (Figure 9). However, a significant proportion of this vegetation is still preserved in high slopes in the Piracicaba basin, and especially in the Alto Paranapanema, with several state parks that encompass a large area of preserved Atlantic Forest.

Riparian buffer zone

The total riparian buffer strip zone (30 m of each stream side) is equal to 6,236 km², which corresponds to approximately 7% of the sum of the area of the seven basins (88,322 km²). From this total of

riparian area approximately 4,646 km², which corresponds to approximately 75%, need to be restored to comply with the law, i.e. only 25% of the total riparian area is indeed covered with riparian vegetation. This proportion varied among the basins (Figure 10). For instance, the riparian vegetation covered only 8% of the buffer strip zone in the São José dos Dourados watershed. In contrast, in the Alto Paranapanema basin approximately 40% of the buffer zone was still covered with riparian vegetation (Figure 10). In addition to these two extremes, in the Turvo and in the Peixe basins original riparian vegetation covers an area equivalent to 25 to 30% of the buffer zone (Figure 10). In the Aguapeí basin, this proportion is reduced to approximately 22%, and in the Piracicaba and the Mogi Guaçu, decreases even more to less than 20% (Figure 10).

Pasture is the main land-cover of the riparian buffer strip zone. This is especially true in the Turvo, the São José dos Dourados, the Aguapeí and Peixe basins. The only exception to this pattern is the Moji-Guaçu basin where sugar cane is the main land-cover of the buffer zone, which in turn, is also important in the Piracicaba basin (Figure 10). The current cost to restore 1 hectare of riparian forest in the Piracicaba Basin was estimated to be approximately R\$ 7,000/ha (US\$ 3,350/ha). Assuming that these values are also valid for other basins, the final cost to restore approximately 4,700 km² of riparian area would be equivalent to a cost of 3.28 billions reais, or 1.57 billion dollars.

Our first research question considered what the major land-cover was in 1997 in certain watersheds. Pasture was the dominant land-cover in the watersheds, dominating almost half of the entire area.

The expansion of the agricultural frontier in the State of São Paulo toward the west resulted in a pat-

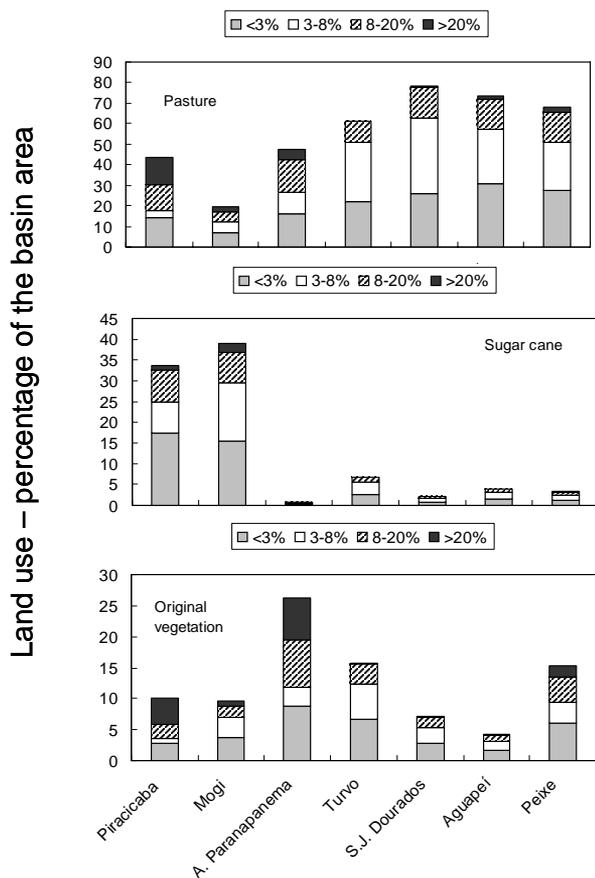


Figure 9 - Occurrence of pasture, sugar cane and original vegetation in classes of slopes in each basin. flat (<3%); smoothly rolling (3-8%); rolling (8-20%) and hilly (>20%).

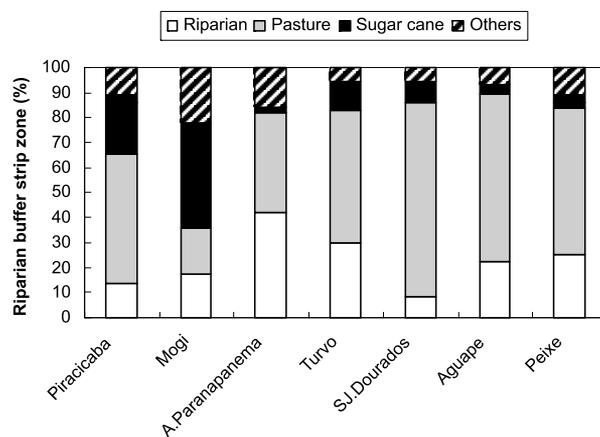


Figure 10 - Land use, expressed in percentage, occurring in the riparian preservation area (30m buffer strip zone for each stream side).

tern of land-cover where the original vegetation was replaced by coffee and cotton, and in turn, these crops by pasture (Webb et al., 2005; Brannstrom & Oliveira 2000; Brannstrom, 2001). The economic reasons for these changes go beyond the main focus of this study, but the Wall Street crash in 1929 together with the loss of fertility due to the erosion process in the Vale do Paraíba, the northeastern region of the State of São Paulo, are among the main causes for such changes.

Land-cover and land-use changes are frequently associated to the production of food, fiber and energy to meet human needs (Lambin et al., 2003). These are key activities for maintaining life and generating wealth. For instance, in 2004 the gross domestic product for agricultural business in the State of São Paulo was equivalent to approximately 34 billion reais or 16 billion dollars (dollar to real ratio of 2.0885, February 23, 2007), equivalent to 6% of the whole gross domestic product of the State. This is a positive impact related to land-cover/use changes. On the other hand, land-cover/use changes also have negative environmental impacts that we briefly discuss below.

The current predominance of pastures in the investigated basins affects several ecological processes. These large areas of pasture limit the movement of the wild life among forest patches for many reasons. For instance, Pires et al. (2002) studied the movement of small mammals (rodents and marsupials) among patches of forest surrounded by grasslands and found that the movement between patches was restricted due to presence of pasture areas. The same seems to be true for top predators, such as the population of *Panthera onca* living in the Morro Diabo State Reserve, located in southwestern the State of São Paulo (Cullen et al., 2005). Another important environmental aspect of pasture land is the risk from the fire, which is intensively used by Brazilian livestock farmers. Pasture fires intensify soil erosion (Bertoni & Lombardi Neto, 1990) and water pollution (Cerri et al., 2001) due the loss of the soil surface cover and the subsequent exposure to erosive rainfall.

The second most important land-cover in the State of São Paulo in 1997 is sugar cane. The main region that sugar cane is cultivated is the central-eastern towards the northwestern regions of the State of São Paulo, mainly in the Piracicaba and Moji-Guaçu watersheds. The sugar cane area in the State of São Paulo comprises approximately 31,600 km², equivalent to 14% the area of the State (Rudorff et al., 2004). In comparison, in 1997 the area planted with sugar cane in the seven watersheds of this study was equal to approximately 12,000 km².

The main ecological and social problem linked to this crop is the burning of sugar cane fields before harvesting each year from May to October (Martinelli & Filoso, 2007). This process leads to serious atmospheric pollution and acid rain (Lara et al., 2001), which may cause further soil acidification (Krusche et al., 2003). In addition to these effects, the amount of air-borne particules also increased with sugar cane burning (Lara et al., 2001; Lara et al., 2005). This increase of air-borne particles caused an increase of respiratory diseases in regions such as Araraquara (Arbex et al., 2000), and Piracicaba (Cançado et al., 2006). In addition, every 5 or 6 years, sugar cane plantations are removed and cultivated again. This type of management requires heavy traffic of machinery in the field, and each year a portion of the planted area is replaced, exposing bare soil for months, increasing the erosion risk (Cerri et al., 2001; Sparovek & Schunug, 2001). Once the erosion risk is higher, it also increases the chances of a higher input of applied fertilizers to streams (Filoso et al., 2003).

One of the most important aspects of land-cover studies is to establish how much of the original vegetation remains for a "biophysical baseline", as defined by Brannstrom (2001). This "biophysical baseline" directly influences the distribution of vegetation and animal species, which ultimately defines the biodiversity of a certain region (Webb et al., 2006). According to our results, in the entire study area, only 15% of the original vegetation remained in 1997.

The highest deforestation rate in the State of São Paulo was observed between 1907 and 1934, when approximately 80,000 km² of original vegetation was lost in the conversion from forest to coffee (Brannstrom, 2000). In the Fifties, only 25% of the original vegetation remained (Vianna & Pinheiro, 1998). In 1962, using aerial photographs, Borgonovi et al. (1967) estimated that this area decreased to 14%, reaching a minimum of approximately 10% in the Eighties (Vianna & Pinheiro, 1998). More recently the Instituto Florestal (2005) estimated that approximately 15% of the area of the State of São Paulo is covered with natural vegetation. It is important to note that in September 15, 1965 the Brazilian Forest Legislation was implemented (Instituto Florestal web site, see references). After this legislation was approved, deforestation was forbidden in many areas, such as in riparian zones, and in areas with slopes steeper than 25%. This law might have diminished the rate of deforestation and probably slightly increased the area of natural reforestation. To illustrate this situation, Toledo (2001) found, between 1962-1995, in two small watersheds, an increase of natural vegetated areas from 19.5% to 34.0%.

The three land-cover classes – pasture, sugar cane, and original forest – discussed above comprised approximately 80% of the entire study area. The first two land classes certainly play an important role in the economy of the State of São Paulo, and the last assumes a fundamental role in several ecological aspects of the landscape. On the other hand, most of the population in the watersheds that were addressed in this study live in urban centers (Table 1). Urban areas cover a small portion of the landscape, but these areas have a disproportional impact in relation to their area either socially or ecologically. Urbanized areas are normally linked to many social-economic and environmental problems (Ojima et al., 1994). Cities become one of the most life-threatening environments on Earth. The concentration of wastes is one of the most important aspects of cities (United Nations, 2003). The 2003 UN report, “Water for People Water for Life” notes that most urban areas have inadequate waste management, especially in developing countries. In the State of São Paulo, although 80% of the domestic sewage is collected, only 17% is effectively treated (Martinelli et al., 2002). Most of the untreated sewage is discarded into rivers and streams seriously impacting ecological and biological integrity (Ometto et al., 2000; Daniel et al., 2002). Therefore, in the most populated areas, such as the Piracicaba and the Mogi Guaçu basins, the water quality of rivers and streams is a major concern.

Our second research question was on how much of the riparian vegetation was still preserved in 1997 in the 30 m-width buffer zone. It is observed that only 25% of this vegetation type was preserved. This lack of conservation in riparian areas is not only occurring in the State of São Paulo. Riparian vegetation has been constantly and directly affected by deforestation worldwide. Riparian zones are important because they frequently harbor a disproportionately higher number of wildlife species and perform a disparate number of ecological functions as compared to most upland habitats (Fischer et al., 2000). Such an ecosystem is among the most productive and richest in biodiversity of the world (Loefering 1999), playing a key role as a corridor for wildlife (Metzger & Décamps, 1997, Metzger 1999). They are usually recognized in facilitating biological fluxes, reducing extinction risks, and providing refuges against disturbances, being essential components of the connectivity of patches in the landscapes among other environmental services (Metzger & Décamps, 1997, Stromberg, 2001, Joly et al., 2001).

Finally our third research question was about the dominant land-cover invading riparian zones. Grasses from pastures are the main type of vegeta-

tion invading these areas in most of the basins, except in the Moji-Guaçu watershed, where sugar cane is the dominant invading vegetation into the riparian zone. Currently there is a government program in the State of São Paulo devoted to restoring riparian vegetation in small basins. This program claims that approximately 145 km² of riparian forest has already been restored (much less than the 4,700 km² that needs to be restored) at an estimated cost of 3.28 billion reais (1.57 billion dollars). In order to put these sums in perspective, we estimated that these costs are equivalent only to 10% of the gross domestic product related to agricultural business of the State of São Paulo in 2004. Not considering the difficulties in restoring riparian areas attributable to the natural complexity plant community structure (Joly et al., 2001), the total cost of restoration is modest as compared to the annual income generated by the agricultural business of the State of São Paulo.

CONCLUSIONS

The land-cover of the State of São Paulo in 1997 was a consequence of economic and social processes that occurred in the past. These processes have led to a clear dominance of pastures and sugar cane plantations in this State, with few areas of original vegetation remaining. These changes in land use had a wide range of environmental impact that was briefly described in this study, including an increase in soil erosion, water pollution, and loss of biodiversity mainly due to landscape fragmentation. Developing countries, such as Brazil, are characterized by dynamic economies, with very rapid and significant changes. These changes lead to important changes in the land-cover of the State of São Paulo. This study, which encompasses an area equivalent to almost 40% of the entire state, opens the interesting possibility of comparing the land-cover in 1997 and the future land-cover of seven major watersheds of the State of São Paulo

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REFERENCES

- ARBEX, M.A.; BOHM, G.M.; SALDIVA, P.H.N.; CONCEIÇÃO G.M.S, POPE, A.C.; BRAGA, A.L. Assessment of the effects of sugar cane plantation burning on daily counts of inhalation therapy. *Journal of Air and Waste Management Association*, v.50, p.1745-1749, 2000.
- BERTONI, J.; LOMBARDI NETO F. *Conservação do solo*. São Paulo: Editora Ícone, 1990. 355p.

- BORGONOV, M.; CHIARINI, J.V.; AMARAL, Á.Z.; COELHO, A.G.S.; OLIVEIRA, D. A. Cobertura vegetal do Estado de São Paulo: II – Levantamento por fotointerpretação das áreas cobertas com floresta natural e reflorestamento. **Bragantia**, v.26, p.93- 102, 1967.
- BRANNSTROM, C. Coffee Labor Regimes and Deforestation on a Brazilian Frontier, 1915-1965. **Economic Geography**, v.76, p.326-346, 2000.
- BRANNSTROM, C. Conservation-with-Development Models in Brazil's Agro-pastoral Landscapes. **World Development**, v.29, p.1345-1359, 2001.
- BRANNSTROM, C.; OLIVEIRA, A.M.S. Human modification of stream valleys in the western plateau of São Paulo, Brazil: implications for environmental narratives and management. **Land Degradation & Development**, v.11, p.535-548, 2000.
- CANÇADO, J.E.; SALDIVA, P.H.N.; PEREIRA, L.A.A.; LARA, L.B.L.S.; ARTAXO, P.; MARTINELLI, L.A.; ARBEX, M.A.; ZANOBETTI, A.; BRAGA, A.L.F. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. **Environmental Health Perspectives**, v.114, p.725-729, 2006.
- CERRI, C.E.P.; DEMATTÊ, J.A.M.; BALLESTER, M.V.R.; MARTINELLI, L.A.; VICTORIA, R.L.; ROOSE, E. GIS Erosion Risk Assessment of the Piracicaba River Basin, Southeastern Brazil. **Mapping Sciences & Remote Sensing**, v.38, p.157-171, 2001.
- CULLEN JR, L.; ABREU, K.C.; SANA, D.; NAVA, A.F.D. Jaguars as landscape detectives for the upper Paraná River corridor, Brazil. **Natureza & Conservação**, v.3, p.43-58, 2005.
- DANIEL, M.H.B.; MONTEBELO, A.A.; BERNARDES, M.C.; OMETTO, J.P.H.B.; CAMARGO, P.B.; KRUSCHE, A.V.; BALLESTER, M.V.; VICTÓRIA, R.L.; MARTINELLI, L.A. Effects on urban sewage on dissolved oxygen, dissolved inorganic and organic carbon, and electrical conductivity on small streams along a gradient of urbanization in the Piracicaba River basin. **Water, Air, and Soil Pollution**, v.136, p.189-206, 2002.
- EASTMAN, J.R. **Idrisi32 - Release 2**: Tutorial. Worcester, Massachusetts: Clark University, 2001. 238p.
- FILOSO, S.; MARTINELLI, L.A.; WILLIAMS, M.R.; LARA, L.B.; KRUSCHE, A.V.; BALLESTER, M.V.; VICTORIA, R.L.; CAMARGO, P.B. Land use and nitrogen export in the Piracicaba River Basin, Southeast Brazil. **Biogeochemistry**, v.65, p.275-294, 2003.
- FISCHER, R.A.; CHESTER, O.M.; FISCHENICH, J.C. Improving riparian buffer strips and corridors for water quality and wildlife. In: INTERNATIONAL CONFERENCE ON RIPARIAN ECOLOGY AND MANAGEMENT IN MULTI-LAND USE WATERSHEDS, Portland, 2000. Middleburg: American Water Resources Association, 2000. 7p. Available at: <http://www.swf.usace.army.mil/pubdata/environ/regulatory/other/links/stream/improvingriparianbufferstrips.pdf>.
- GROppo, J.D.; MORAES, J.M.; MARTINELLI, L.A.; GENOVEZ, A.M. Estudo de Tendência de Parâmetros de Qualidade de Água na Bacia do Rio Piracicaba. **Revista Brasileira de Recursos Hídricos**, v.11, p.79-87, 2006.
- HOUGHTON, R.A. The worldwide extent of land-use change. **Bioscience**, v.44, p.305-313, 1994.
- INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA - IBGE-. **Base de informações Municipais**. 3.ed. Rio de Janeiro, 2002. 1 CD-ROM.
- INSTITUTO FLORESTAL. **Inventário florestal da vegetação natural do Estado de São Paulo**. São Paulo: Secretaria do Meio Ambiente; Instituto Florestal, Imprensa Oficial, 2005. 200p.
- JOLY, C.A.; SPIGOLON, J.R.; LIEBERG, S.A.; SALIS, S.M.; AIDAR, M.P.M.; METZGER, J.P.W.; ZICKEL, C.S.; LOBO, P.C.; SHIMABUKURO, M.T.; MARQUES, M.C.M.; SALINO, A.. Projeto Jacaré-Pepira – O Desenvolvimento de um modelo de Recomposição da Mata Ciliar com base na Florística Regional. In: RODRIGUES, R.R.; LEITÃO FILHO, H.F. (Ed.). **Matas ciliares, conservação e recuperação**. São Paulo: EDUSP; FAPESP, 2001. p.271-287.
- KRONKA, F.J.N. **Inventário Florestal das Áreas Reflorestadas do Estado de São Paulo**. São Paulo, SP. São Paulo: Secretaria do Meio Ambiente; Instituto Florestal, 2002. 184p.
- KRUSCHE, A.; CAMARGO, P.B.; CERRI, C.E.; BALLESTER, M.V.; LARA, L.; VICTORIA, R.L.; MARTINELLI, L.A. Acid rain and nitrogen deposition in a sub-tropical watershed (Piracicaba): ecosystems consequences. **Environmental Pollution**, v.121, p.389-399, 2003.
- LAMBIN, E.F.; GEIST, H.J.; LEPERS, E. Dynamics of land-use and land-cover change in tropical regions. **Annual Review of Environmental Resources**, v.28, p.205-241, 2003.
- LARA, L.B.S.L.; ARTAXO, P.; MARTINELLI, L.A.; VICTORIA, R.L.; CAMARGO, P.B.; KRUSCHE, A.; AYERS, G.P.; FERRAZ, E.S.B.; BALLESTER, M.V. Chemical composition of rain water and anthropogenic influences in the Piracicaba River basin, southeast Brazil. **Atmospheric Environment**, v.35, p.4937-4945, 2001.
- LARA, L.L.; ARTAXO, P.; MARTINELLI, L.A.; CAMARGO, P.B.; VICTORIA, R.L.; FERRAZ, E.S.B. Properties from aerosols from sugar cane burning emissions in Southeastern Brazil. **Atmospheric Environment**, v.39, p.4627-4637, 2005.
- LILLESAND, T.M.; KIEFER, R.W. **Remote sensing and image interpretation**. 4.ed. New York: John Willey & Sons, 2000. 724p.
- LOEGERING, J. Why are riparian zones biologically diverse? 1999. Available at: http://www.orst.edu/instruct/fw251/modules/wetlands/rip_biodiversity.htm
- MANDER, Ü.; KULL, A.; KUUSEMENTS, V.; TAMM, T. Nutrient dynamics in a rural catchment: Influence of land-use changes, climatic fluctuations and ecotechnological measures. **Ecological Engineering**, v.14, p.405-417, 2000.
- MARTINELLI, L.A.; SILVA, A.M.; CAMARGO, P.B.; MORETTI, L.R.; TOMAZELLI, A.C.; SILVA, D.M.L. da; FISCHER E.G.; SONODA, K.C.; SALOMÃO, M.S.M.B. Levantamento das cargas orgânicas lançadas nos rios do Estado de São Paulo. **Biotaneotropica**, v.2, p.1-18, 2002.
- MARTINELLI, L.A.; FILOSO, S. Polluting effects of Brazil's sugar-ethanol industry. **Nature**, v.445, p.364-364, 2007.
- METZGER, J.P. Estrutura da paisagem e fragmentação: Análise bibliográfica. **Anais da Academia Brasileira de Ciências**, v.71, p.445- 463, 1999.
- METZGER, J.P.; DÉCAMP, H. The structural connectivity threshold: an hypothesis in conservation biology at a landscape scale. **Acta Ecologica**, v.18, p.1-12, 1997.
- OJIMA, D.S.; GALVIN, K.A.; TURNER II, B.L. The Global Impact of Land-Use Change. **Bioscience**, v.44, p.300-304, 1994.
- OMETTO, J.P.H.B.; MARTINELLI, L.A.; BALLESTER, M.V.; GESSNER, A.; KRUSCHE, A.V.; VICTÓRIA, R.L.; WILLIAMS, M. Effects of land use on water chemistry and macroinvertebrates in two streams of the Piracicaba River basin, south-east Brazil. **Freshwater Biology**, v.44, p.327-337, 2000.
- PIRES, A.S.; KOELER, P.; LIRA, F.A.S.F.; SCHITIINI, G.M.; OLIVEIRA, L.C. Frequency of movements of small mammals among Atlantic Coastal Forest fragments in Brazil. **Biological Conservation**, v.108, p.229-237, 2002.
- RUDORFF, B.F.T.; BERKA, L.M.S.; MOREIRA, M.A.; DUARTE, V.; ROSA, V.G.C. **Estimativa de área plantada com cana-de-açúcar em municípios do Estado de São Paulo por meio de imagens de satélites e técnicas de geoprocessamento: ano safra 2004/2005**. São José dos Campos: INPE, 2004. 54p. (INPE-11421-RPQ/762).
- SANTOS, R.D.; LEMOS, R.C.; SANTOS, H.G.; KER, J.C.; ANJOS, L.H.C. **Manual de descrição e coleta de solo no campo**. 5.ed. Viçosa: SBCS, 2005. 92p.
- SPAROVEK, G.; SCHNUG, E. Temporal erosion-induced soil degradation and yield loss. **Soil Science Society of America Journal**, v.65, p.479-1486, 2001.
- STROMBERG, J.C. Restoration of riparian vegetation in the south-western United States: importance of flow regimes and fluvial dynamism. **Journal of Arid Environments**, v.49, p.17-34, 2001.

- TOLEDO, A.M. Evolução espaço-temporal da estrutura da paisagem e sua influência na composição química das águas superficiais dos ribeirões Piracicamirim e Cabras (SP). Piracicaba: USP/ESALQ, 2001. 94p. (Master Science Thesis).
- VIANNA, V.M.; PINHEIRO, L.A.F.V. Conservação da biodiversidade em fragmentos florestais. **Série Técnica IPEF**, v.12, p.25-42, 1998.
- VITOUSEK, P.M.; MOONEY, H.A.; LUBCHENCO, J.; MELILLO, J.M. Human domination of earth's ecosystems. **Science**, v.277, p.494-499, 1997.
- UNITED NATIONS WORLD WATER DEVELOPMENT REPORT. **Water for people - water for life**. Barcelona: UNESCO; Berghahn Books, 2003. 575p.
- WEBB, T.J.; WOODWARD, I.; HANNAH, L.; GASTON, K.J. Forest cover-rainfall relationships in a biodiversity hotspot: the Atlantic Forest of Brazil. **Ecological Applications**, v.15, p.1968-1983, 2005.
- WEBB, T.J.; GASTON, K.J.; HANNAH, L.; WOODWARD, I. Coincident scales of forest feedback on climate and conservation in a diversity hot spot. **Proceedings of The Royal Society B**, v.273, p.757-765, 2006.

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