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FOREST CONVERSION AND PROVISION OF ECOSYSTEM SERVICES IN THE BRAZILIAN ATLANTIC FOREST

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ABSTRACT

The importance of quantifying existing ecosystem services, assessing the impacts of various land use decisions and ultimately evaluating the overall costs and benefits of different land use patterns having internalized ecosystem services, is now widely recognized and such work is at the forefront of current landscape management planning. We aim to quantify ecosystem services derived from different land uses within the Atibainha Reservoir catchment in Brazil, determine the spatial distribution of ecosystem services and quantify the impacts of land use changes on the provision of ecosystem services. Four ecosystem services were considered: carbon sequestration, mitigation of sediment delivery into the reservoir, purification of water and maintenance of soil fertility. Results indicate strong increase in the provision of ecosystem services among the main land uses in the following order: urban area/bare soil; pastures; plantation of eucalyptus and native forests. The most important services provided by native forests, when compared with bare soil, were carbon sequestration and prevention of sedimentation, with an additional 864 569 tons of carbon stored in forest biomass in 30 years, and prevention of 244 511 tons of sediment delivery into the reservoir per year, respectively, from 7624 ha of lands around the reservoir. Spatial variation in the provision of ecosystem services were mapped to develop a tool to support decision making at the landscape scale. Results and maps from the decision support tool can support policies that ensure effective land-use planning and can serve as the basis for the development of payment for ecosystem service schemes in the region. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: ecosystem services; Atlantic forest; land use changes; environmental services; Brazil

INTRODUCTION

There is increasing concern about losses of ecosystem services due to conversion of native forests into urban areas, forestry plantations, agriculture and pastures in already degraded biomes such as the Brazilian Atlantic Forest. However, there are few attempts to model variations in the provision of ecosystem services (EPA, 2009). Forecasting the impacts of landscape changes on these services is necessary for the development of innovative mechanisms that may reverse the current levels of habitat loss and fragmentation of ecosystems (Tabarelli *et al*., 2005). Preventing forest loss is particularly relevant to lands that provide ecosystem services to major conurbations where half of the world's population currently live and where more than 5 billion people will be living by 2030 (UNFPA, 2008). One such conurbation is the city of São Paulo, home to 19 million inhabitants, and located within the limits of the Atlantic Forest biome in southeastern Brazil (Silvano *et al*., 2005). More than 50% of São Paulo city relies on the water supply system known as Cantareira. This system is formed by six reservoirs, whose watersheds cover 228 000 ha of land in 12 municipalities. Currently, the Cantareira System is able to supply 33 000 L of water per second (Whately and Cunha, 2007).

Inappropriate land uses in the Atlantic Forest region threatens the continued provision of clean water within the Cantareira System (Braga, 2001), an issue of great concern considering rapidly growing demands on water resources from growing urban populations.

The Atibainha Reservoir, in the municipality of Nazaré Paulista, is one of six lakes within the Cantareira System. Since the 1970s, when the reservoir was built, the picturesque landscape formed by the surrounding hilly land, remnants of Atlantic Forest and abundance of water, has been attracting people from neighbouring towns and cities, including São Paulo. The landscape has changed as a consequence of the arrival of short-term visitors and new residents in the region. New immigrants have placed further pressure on the land through expansion of pasture and eucalyptus plantations, as well as illegal clearing of native

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forest for settlements (Fadini and Carvalho, 2004). Landscape conversion is likely to impact the provision of ecosystem services derived from native forest remnants. Assessment and quantification of ecosystem services can be useful for determining the extent to which these changes in land use affect human well being.

Previous studies attempted to estimate values of ecosystem services associated with the presence of native forests in Mexico (Adger *et al*., 2002), China (Guo *et al*., 2001; Li *et al*., 2006; Chen *et al*., in press), Costa Rica (Bernardt *et al*., 2009), in the Brazilian Amazonian Forest (Torras, 2000) and the entire planet (Costanza *et al*., 1997). Despite the fact that the Brazilian Atlantic Forest has been highly degraded due to unplanned land use, there are few attempts to study losses of ecosystem services in this biome.

In this study we consider four services derived from the Atlantic Forest biome that are relevant to local farmers' land productivity, water security for regional downstream consumers and to the international community in terms of mitigation of climate change. Specifically, these services are maintenance of soil fertility, mitigation of sedimentation of the reservoir, purification of water and carbon sequestration. These services are called 'ecosystem processes' by some authors concerned with the distinction between means and ends in the classification and definition of concept of ecosystem services (Wallace, 2007; Fisher and Turner, 2008).

Maintenance of soil fertility is a precondition for biogeochemical processes and elemental cycles that occur in the soils of both cultivated lands and natural forests (CSIRO Sustainable Ecosystems, 2003). Preventing sedimentation is necessary to maintain the capacity of water storage in reservoirs in the long term. The role played by forests in purifying the water can be helpful in water supply systems. Finally, the ability of plants to capture carbon from atmosphere is crucial for climate regulation.

Estimates of these services under different land use scenarios are necessary to underpin future land use decision making to ensure optimal land use benefits and ecosystem service provision.

Thus the objectives of this study are to: (1) quantify the value of ecosystem service provision under different land uses and land use scenarios; (2) determine the spatial distribution of ecosystem services in current land use scenarios; (3) quantify the impacts of land use changes on the availability of ecosystem services and (4) determine the extent to which human welfare can be affected by land use policies due to gains and losses of ecosystem services.

METHODOLOGY

Study Area

The study area includes 188 catchments that surround the Atibainha Reservoir (Figure 1). They occupy 25% of the municipality of Nazaré Paulista (at 23°9′S on 46°20′W) and less than 1% of the municipality of Piracaia. The total area excluding the reservoir is 7624 ha. There are approximately 200 streams narrower than 2 m in these catchments, flowing into the reservoir. Steep slopes, with declivity higher than 25 degrees, predominate in the region and altitudes vary from 785 m above sea level, which is the height of the reservoir, to 1160 m at the hilltops.

The 'argissolo vermelho-amarelo' (Arenic Hapludult) is the soil encountered in most of the study area. The 'latossolo vermelho-amarelo' (Humic Hapludox) can also be found but over a smaller area (Oliveira *et al*., 1999). Fragments of Atlantic Forest occupy 46% of the area, followed by pastures (27%), eucalyptus forests (10%) and other uses (17%). Most of the native forests are secondary and older than 15 years, with canopies taller than 10 m (Ditt *et al*., 2008).

Cattle are grazed in the pastures mostly for the production of milk by small farms with low productivity and low technology. Eucalyptus plantation is one of the most profitable activities in the region and has been expanded on small properties (Fadini and Carvalho, 2004).

Mapping Ecosystem Services and Scenario Analysis

An analysis of the different land use scenarios was used to determine how the availability of ecosystem services is affected by changes in land use. The ecosystem services were quantified and mapped in the study area for the current land use scenario (S1) and for four possible future land use scenarios (S2, S3, S4 and S5). The current land use scenario (S1) refers to heterogeneous landscape with 46% of native forest, 27% of pastures, 10% of eucalyptus and 9% of bare soil or urbanized areas. The four possible future land use scenarios refer to homogeneous landscape with 100% of pastures (S2), 100% of eucalyptus (S3), 100% of native forests (S4) and 100% of bare soil or urban areas (S5).

These future scenarios represent homogeneous landscapes that could occur 30 years into the future, that is in 2039, resulting from the maximum expansion of each of the four main land uses (native forest, eucalyptus, pasture and urban area/bare soil). While these may not be entirely realistic future outcomes, they are presented here by way of comparison.

Each of the ecosystem services required a specific method of assessment as described below. GIS layers in the format of a shape file were constructed to express results of the assessments on a geo-referenced basis for further analysis of scenarios of land use change. The analysis was applied to both the entire study area composed of all the catchments and to each individual catchment.

Estimation of Carbon Stocks

Estimates of the capacity of forest ecosystems to sequester and store carbon in biomass are helpful for quantifying their

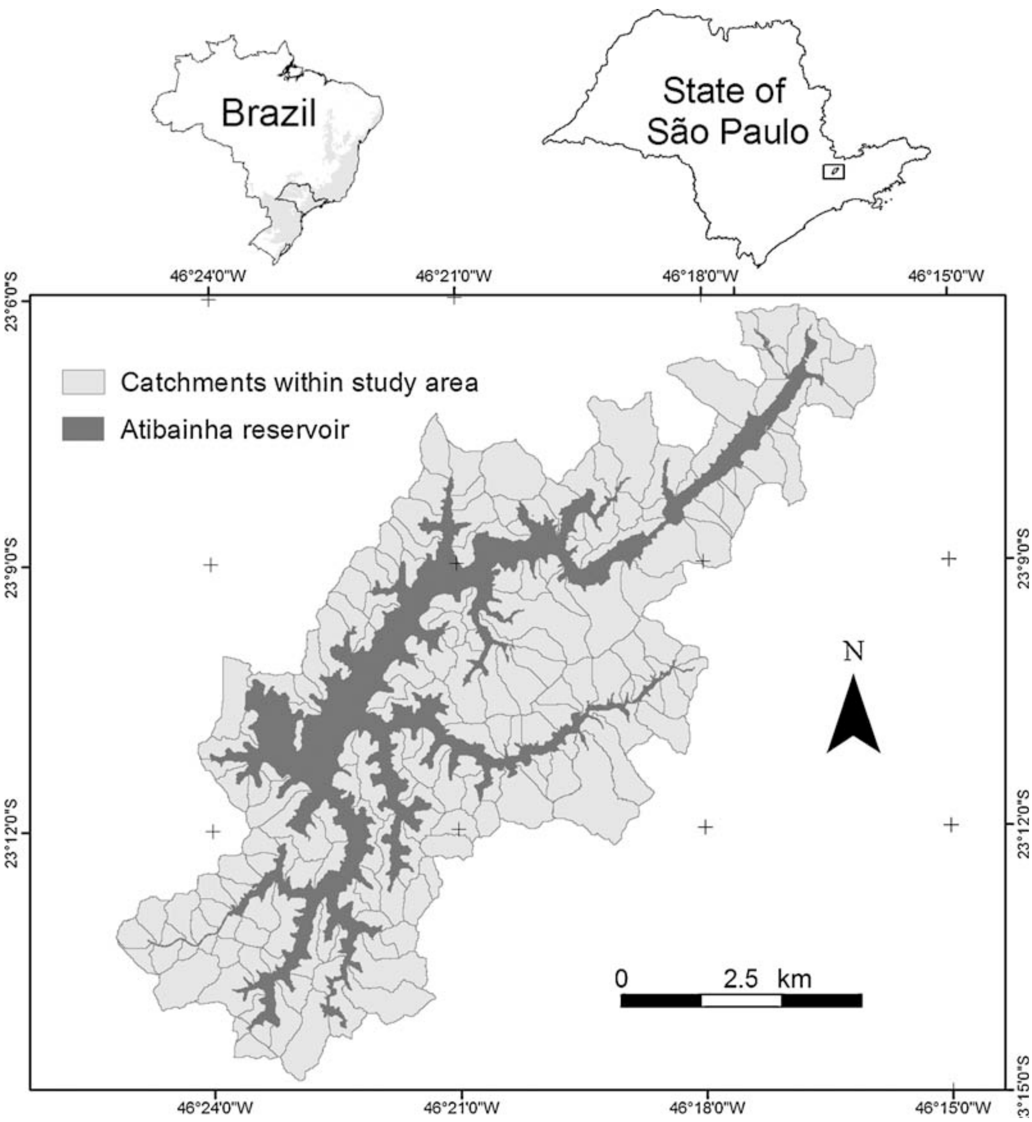

Figure 1. Study area, composed by catchments that surround the Atibainha Reservoir in eastern São Paulo State (source: Ditt *et al*., 2008).

potential contribution for climate change mitigation because they indicate how much carbon dioxide, a greenhouse gas, would be released in the atmosphere if the forests were not present. Four main carbon pools may be considered: above ground plant biomass, below ground biomass, soils and standing litter. The first of these is the most easily manipulated carbon pool in carbon storage forest projects (MacDicken, 1997). In several studies the above ground plant biomass in native forests has been estimated from data obtained in field surveys of vegetation, including: number of trees per area, species, wood density, diameters of trees and height of trees (Brown *et al*., 1989; Burger and Delitti, 1999; IPEF, 2006; Melo and Durigan, 2006).

In this research the benefits of climate mitigation derived from the maintenance of carbon stocks in the trees above ground were determined for the main land uses in the study area through estimates of biomass. Four categories of land use were considered: eucalyptus; pastures/bare soil; younger native forest (F1) and older native forest (F2). The two classes of native forests (F1 and F2) were previously defined by Ditt *et al.* (2008) and could be distinguished through visual classification of aerial photograph and stereoscopy.

Field sampling of native vegetation was developed in ten areas of forest F1 and in ten areas of forest F2. The quarter point method (Martins, 1993) was used to collect data for the following variables: distance of the trees from the sampling points of the quadrants; and diameter of their trunks at 1·30 m above ground. Twenty sampling points were established in each area. Each sampling point was composed of four quadrants, giving 80 quadrants and 80 trees measured.

The most appropriate threshold value of trunks' perimeter for sampling trees that compose the canopy in the forests of the study area was considered to be 17 cm according to observations during the fieldwork. Therefore, only trees with circumference higher than this value were measured.

The area occupied by each tree was determined through calculation of the squared distance of the trees from each sampling point, according to the quarter point method.

The above ground biomass per tree was calculated using a regression Equation suggested by Brown (1997) for tropical forests in moist zones. The Equation is expressed by:

$$Y = \exp\{-2 \cdot 134 + 2 \cdot 530 \times \ln(D)\},$$

where: Y (kg) = biomass per tree and D (cm) = diameter of trunk at 1·3 m above ground.

The above ground forest biomass density in tons of biomass per hectare was calculated from the sum of the estimated area occupied by the sampled trees and the sum of the above ground biomass of the sampled trees.

The below ground tree biomass was calculated using the following regression model suggested by Pearson *et al.* (2005):

$$\mathrm{BBD} = \exp(-1 \cdot 0587 + 0 \cdot 8836 \times \ln \mathrm{ABD}),$$

where: BBD = below ground biomass density and ABD = above ground biomass density.

Finally, it was assumed that carbon corresponds to 50% of forest biomass, as suggested by Brown and Lugo (1984). Therefore estimated values of biomass in forests F1 and F2 were divided by 2 to determine their respective estimates of above ground carbon stocks per hectare.

The capacity of eucalyptus plantations to accumulate carbon in the above ground biomass in 6 years, estimated by Paixão *et al*. (2006), is 47·7 tons ha^{-1}. This value was used in the current study for determining the extent to which eucalyptus contribute to the mitigation of climate change. It was assumed that the eucalyptus is regularly harvested every 6 years (State Agency of Agriculture of Nazaré Paulista/ Camila Toledo, personal communication), and the accumulation of carbon in biomass is linear over the 6 years. Thus, the obtained average stock of carbon that is maintained in eucalyptus plantations during the cycle of 6 years is 41·66% of the estimated 47·7 tons ha^{-1}, that is 19·87 tons ha^{-1}.

This study has focused only on the carbon stocks in the biomass of trees, therefore in pastures and in areas with soil prepared for agriculture these stocks of carbon were considered negligible.

Estimation of Sediment Delivery

Models that predict erosion and sediment yield can be used for assessing effects of land management on soil and water. One of the most used models is the universal soil loss equation—USLE (Wischmeier and Smith, 1978; Bacchi *et al*., 2003). An important limitation of USLE is that it does not predict deposition and sediment yields (Croke and Nethery, 2006). This limitation is overcome by using the modified universal soil loss equation—MUSLE (Williams, 1975), which was developed subsequently and has been used for estimating sediment deposition in catchments.

The MUSLE was used in this study to quantify the contribution of each catchment for delivering sediments into the reservoir in the five land use scenarios considered. The model is expressed by the following Equation (Williams, 1975):

$$Y = [89 \cdot 6 \times (Q\mathrm{q})^{0.56}]KLSCP,$$

where: Y = event sediment yield, Q = runoff amount, q = peak runoff rate, K = soil erodibility factor, L = slope length factor, S = slope steepness factor, C = cover and management factor and P = support practice factor.

The runoff amount (Q) was calculated for every day in a period of 20 years—from 1984 to 2003—using the Equation suggested by Chaves and Piau (2006), which is:

$$Q = \frac{\mathrm{pa} - 0.2[(25\,400/\mathrm{CN}) - 254]^2}{\mathrm{pa} + 0.8[(25\,400/\mathrm{CN}) - 254]}.$$

The curve number (CN) is a parameter determined by hydrological soil group, land use, treatment, hydrological condition and antecedent runoff condition (USDA, 1986). The values of CN adopted for pasture, eucalyptus, native forest and urban areas were 69, 60, 43 and 82, respectively, as suggested by Bertoni and Lombardi-Neto (2005). The values of daily precipitation (pa) were obtained from the database of the state government, accessible through the Internet (www.sigrh.sp.gov.br, 11/08/2008).

The peak runoff rate (q) was calculated through the equation:

$$q = \frac{0.0021QA}{T_\mathrm{p}} \quad \text{(Chaves and Piau, 2006)},$$

where: A = the area of the catchment and T_p = to the peak duration.

The value of 'T_p' is calculated through the equation:

$$T_\mathrm{p} = \frac{D}{2} + \frac{L}{3.28}^{0.8} \{[(25\,400/\mathrm{CN}) - 254] + 1\}^{0.7} \times \{(1900[y^{(1/2)}])\},$$

where: D = the duration of the precipitation, expressed in hours, L = the length of the catchment and y = the average slope, expressed as a percentage.

Values of erodibility factor (K) suggested by Bertoni and Lombardi-Neto (2005) for 'Podzolizados Lins e Marília, variação Lins' (K = 0·035) and 'Solos de Campos do Jordão' (K = 0·015) were used for the catchments of the study area where 'argissolo vermelho-amarelo' (Arenic Hapludult) and 'latossolo vermelho-amarelo' (Humic Hapludox) prevail, respectively.

Calculation of the slope length factor (L) was based on procedures suggested by Silva (2003) as explained below:

i. Topographical maps of the study area at a scale 1:10·000, published by the Brazilian Institute of Geography and Statistics (IBGE, 1978), with altitude lines in intervals of 10 m were digitized using ArcMap.
ii. A raster digital elevation model (DEM) with cells of 10 m was produced from the digitized altitude lines.
iii. The DEM was used to produce a slope grid map with cells of 10 m, expressing slope (s) in percentage.
iv. The grid cells were classified in four intervals of slope for further attributing slope coefficient values (m), according to the following criteria: $m = 0{\cdot}5$ ($s \geq 5\%$); $m = 0{\cdot}4$ ($3\% \leq s < 5\%$); $m = 0{\cdot}3$ ($1\% \leq s < 3\%$); $m = 0{\cdot}2$ ($s < 1\%$).
v. The eight-direction pour point model (Maidment, 2002) was applied using ArcHydro—an extension of ArcMap—to produce a flow direction grid (x), with cell values of 1, 2, 4, 8, 16, 32, 64 and 128, representing the flow of water in one of the following directions, respectively: E, SE, S, SW, W, NW, N and NE.
vi. A flow accumulation grid was produced from the flow direction grid. The number of flow accumulation assigned to each pixel refers to the number of contributing pixels.
vii. The values of flow accumulation were multiplied by the area of each pixel ($10 \times 10 = 100\,\mathrm{m}^2$) for producing a map of contribution area.
viii. The map of slope length factor (L) was created by applying to each cell the Equation $L = [(A + D^2)^{m+1} - (A)^{m+1}]/[D^{m+2}x^m(22 \cdot 13)^m]$, where, A = contribution area, D = cell size = 10 m, m = slope coefficient value and x = flow direction value.

A grid map of slope steepness factor (S) was created using the following Equation of Wischmeier and Smith (1978): $S = 0 \cdot 00654s^2 + 0 \cdot 0456s + 0 \cdot 065$, where s = mean slope in the catchment, expressed in percentage.

The cover management factor (C) and the support practice factor (P) reflect effects of cropping and management practices on erosion rates and soil loss. The following values of 'C' and 'P' were found in literature (Wischmeier and Smith, 1978; Silva *et al*., 2003; Bertoni and Lombardi-Neto, 2005) and applied in this study: 0·01 and 0·4 for pasture; 0·001 and 0·01 for native forest; 0·003 and 0·04 for reforestation; 1 and 1 for bare soil or urban area.

Among the land uses considered in the study, bare soil/urban area was supposed to be the least effective in preventing sediment delivery into the reservoir. Therefore, it became the reference land use scenario for determining the additional benefits associated with native and eucalyptus forests in preventing sediment delivery. The following Equations were defined to calculate these benefits:

$$\mathrm{PSDf} = \mathrm{ESDu} - \mathrm{ESDf},$$
$$\mathrm{PSDe} = \mathrm{ESDu} - \mathrm{ESDe}, \; -- >$$
$$\mathrm{PSDp} = \mathrm{ESDu} - \mathrm{ESDp},$$

where: PSDf = additional prevention of sediment delivery by native forest, ESDu = estimated sediment delivery in catchments occupied by urban area/bare soil, ESDp = esti-estimated sediment delivery in catchments occupied by pasture, ESDf = estimated sediment delivery in catchments occupied by native forests, PSDe = additional prevention of sediment delivery by eucalyptus and ESDe = estimated sediment delivery in catchments occupied by eucalyptus.

Assessment of Water Quality

Several studies demonstrate effects of land use on the quality of water (Johnson *et al*. 1997; Quinn and Stroud, 2002; Allan, 2004; Shineni, 2005). Nutrients such as nitrite, nitrate and orthophosphate are commonly measured as they are more concentrated in predominantly agricultural and urban catchments compared with forested catchments (Johnson *et al*., 1997). Therefore, determining the relationship between land use and these chemical parameters is a way to quantify the services played by forests in water purification.

Thirty-seven streams around the Atibainha Reservoir were randomly selected for assessment of water chemistry in each of the four seasons of the year. Field kits were used to collect samples of water for measurements of phosphate (PO_4); nitrite (NO_2-N); nitrate (NO_3); alkalinity; Cl; Fe; pH and ammonium (N-NH_3).

Regression analysis was used to determine the degree to which the proportion of forests, eucalyptus and pastures in the uplands influence water chemistry in streams. Considering that the width of buffer areas of streams where land use may influence water chemistry is unknown, the values of land use proportion, that is the independent variable, were calculated in three possible buffer zones: 30, 100 and 200 m around the streams. ArcMap® was used to delineate these buffers and to calculate the land use proportions.

Assessment of Variations in Soil Fertility

Soil fertility has received much attention due to its importance for agricultural productivity (Pulleman *et al*., 2000). However, fertility is not just important for agriculture purposes. Humans obtain many other benefits from the maintenance of soil fertility. Biogeochemical processes and elemental cycles that occur in the soils of both cultivated lands and natural forests depend on their fertility (CSIRO Sustainable Ecosystems, 2003).

Land use change that causes soil fertility to decline will have knock-on effects for other ecosystem services (Reid *et al*., 2005). The impacts on the life of plants are reflected in the services associated with the forest such as carbon storage, watershed protection and ecotourism, among others.

Procedures for the chemical analysis of soil were originally developed for the purpose of determining fertilizer and lime recommendations in agriculture but can equally well be used for evaluating the effects of land management. To produce these recommendations, agronomists often follow the guidelines of the 'Technical Bulletin 100' issued by the Agronomic Institute of Campinas (Van-Raij *et al*., 1997).

The most common parameters considered are organic matter, pH, CEC and levels of macro- and micronutrients (Van-Raij, 1991; Van-Raij *et al*., 1997). They have already been applied in studies for evaluating responses of soil quality to land management (Garcia-Montiel *et al*., 2000; Schipper and Sparling, 2000; Krishnaswamy and Richter, 2002; Sauer and Meek, 2003). Therefore, these parameters can be useful for studies of ecosystem services that depend on soil fertility.

Twenty areas of native forests, ten areas of pastures and ten areas of eucalyptus within the boundaries of 'argissolo vermelho amarelo' (Arenic Hapludult) were randomly selected and sampled for assessing the effects of land use on soil fertility. The lands occupied by 'latossolo vermelho-amarelo' (Humic Hapludox) were neglected in the assessment of soil fertility because of their relative small coverage. As previously, the native forests were divided in two groups ('F1' corresponding to younger forests and 'F2' corresponding to older forests). Twenty sub-samples of soil were collected 20 m from each other in each sampled area at two depths: from 0 to 20 cm and from 40 to 60 cm. Every group of 20 sub-samples was mixed for further extraction of a unique sample of each area. The samples of soil were sent to the laboratory of the Agronomic Institute of Campinas for analysis of pH, cation exchange capacity (CEC), content of organic matter and contents of micro- and macronutrients. The methods and procedures of chemical analysis of soil adopted by the laboratory are detailed by Van-Raij (1991).

Analysis of variance (ANOVA) was initially used to compare means of the chemical parameters among the land uses. The Scheffé's test was used for *posthoc* multiple comparisons when significant differences were detected in ANOVA.

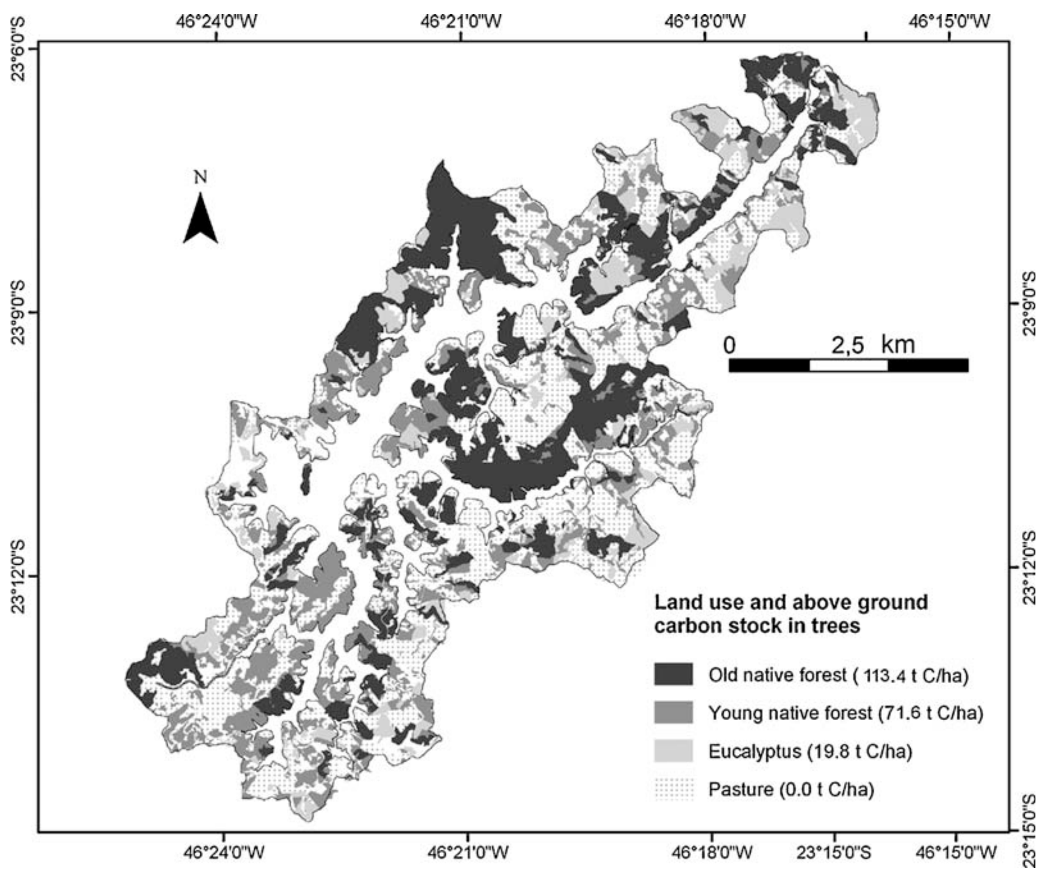

Figure 2. Above ground stocks of carbon in trees per unit of area, estimated for each of the main land uses.

Table I. Carbon stocks in the main land uses around the Atibainha Reservoir

Land use	Area (ha)	Above ground carbon stock in trees per hectare ($t\,ha^{-1}$)	Total above ground carbon stock in trees (t)
Younger native forest (F1)	1774·78	71·60	127 074
Older native forest (F2)	2099·78	113·43	238 178
Reforestation	794·55	19·8	15 732
Pasture	2352·96	0	0
Other uses (without forest)	602·00	0	0
Total	7624·07	—	380 984

A GIS layer was created to indicate areas that could be distinguished by the effects of land use on soil fertility, according to the results of the multiple comparisons performed with the Scheffé's test.

RESULTS

Land Use and Carbon Stocks

Results obtained from the calculation of forest biomass indicated that in older forest (F2) the average carbon storage is $113{\cdot}4\,t\,C\,ha^{-1}$ and in younger forest (F1) it is $71{\cdot}6\,t\,C\,ha^{-1}$. These values and the estimate of $19{\cdot}8\,t\,C\,ha^{-1}$ found in literature for eucalyptus are used to illustrate the carbon storage per unit of area in each land use in the map of Figure 2.

The total stock of carbon in trees biomass, estimated in the current land use scenario of the study area, is 380 984 tons. Of these, 127 074 tons are stored in forests F1, 238 178 tons

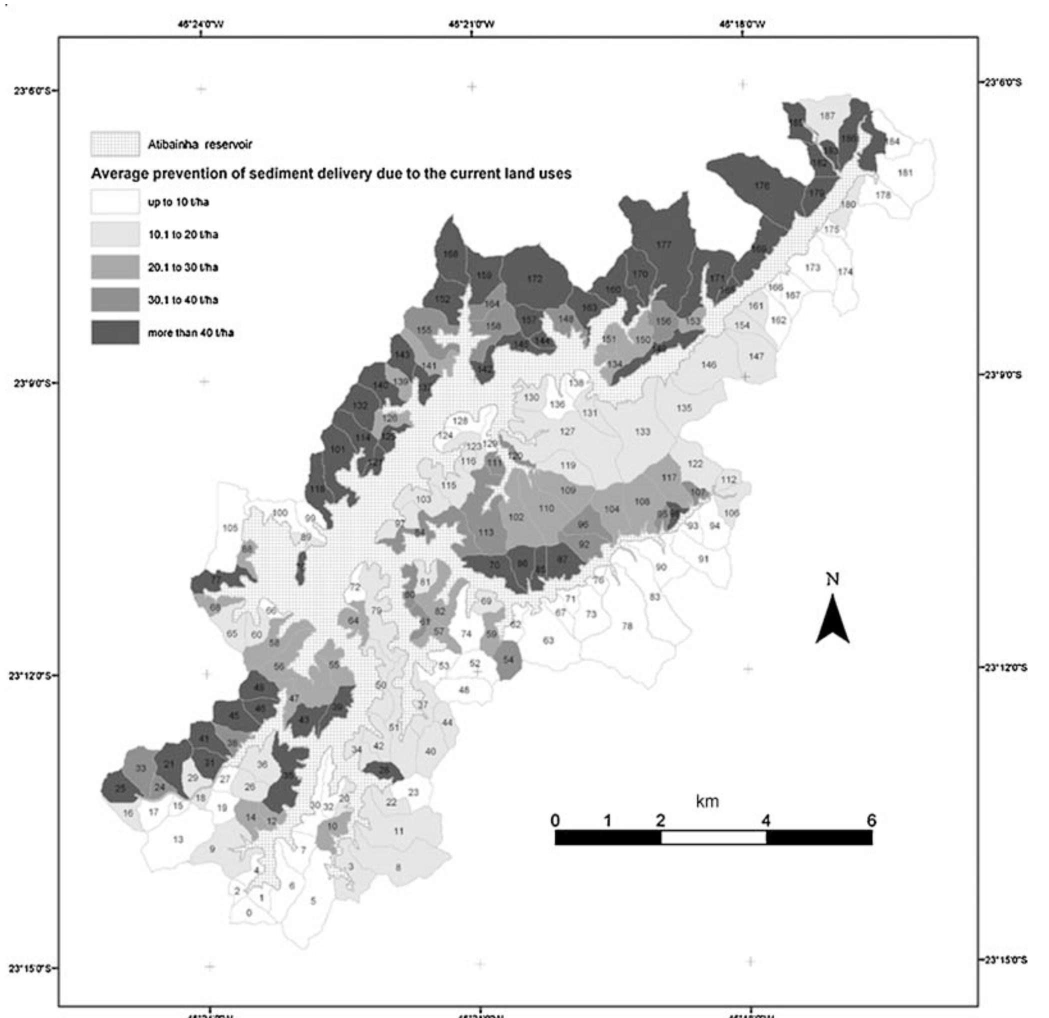

Figure 3. Classification of the catchments according to the average prevention of sediment delivery in the reservoir per unit of area ($t\,ha^{-1}$).

Table II. Significant correlations between land use and water chemistry in buffer zones of 30, 100 and 200 m around streams

Buffer (m)	Land use	Season	R^2	Adjusted R^2	F	p
30	Native forest	Autumm	0·186	0·163	8·006	0·008
30	Native forest	Winter	0·159	0·135	6·608	0·015
30	Pasture	Summer	0·147	0·123	6·045	0·019
30	Pasture	Winter	0·17	0·147	7·183	0·011
100	Native forest	Autumm	0·156	0·132	6·454	0·016
100	Native forest	Winter	0·194	0·171	8·433	0·006
100	Pasture	Summer	0·18	0·156	7·678	0·009
100	Pasture	Winter	0·176	0·152	7·478	0·01
200	Native forest	Autumm	0·16	0·136	6·665	0·014
200	Native forest	Winter	0·16	0·136	6·662	0·014
200	Pasture	Summer	0·166	0·143	6·988	0·012
200	Pasture	Winter	0·139	0·115	5·657	0·023

are stored in forests F2, and 15 732 tons are stored in eucalyptus (Table I).

The total value of carbon stock in trees biomass can change to 864 596, 150 957 and 0 t in the next 30 years, if the landscape is entirely converted to native forest (F2), eucalyptus or pasture, respectively.

Land Use and Sediment Delivery in the Reservoir

The annual estimates obtained through MUSLE of sediment delivered in the reservoir in homogeneous land use scenarios in the 188 catchments are 244 520 tons for urban area/bare soil, 1483 tons for pastures, 67 tons for eucalyptus and 9 tons for native forests.

These results indicate how the capacity of native forests, pastures and eucalyptus to prevent sediment delivery varies among catchments (see Table A1 in Appendix A for a complete list of the catchments with their respective estimates of sedimentation under the various land uses). The last column of Table A1 (Appendix A) indicates the total prevention of sediment delivery that was obtained through multiplication of the proportion of each land use within each catchment by the respective rate.

Table III. Results of analysis of variance for comparing soil fertility in different land uses at different sampling depths

Effect	Response variable	SS	DF	MS	F	p
Land use	Organic matter	1914·6	3	638·2	9·721	0·000017
Depth	Organic matter	13546·0	1	13 546	206·335	0·000000
Land use	P	71·072	3	23·691	2·1271	0·103866
Depth	P	1336·613	1	1336·613	120·0114	0·000000
Land use	K	3·3926	3	1·1309	4·2163	0·008232
Depth	K	12·8801	1	12·8801	48·0216	0·000000
Land use	Ca	361·186	3	120·395	4·5361	0·005620
Depth	Ca	405·000	1	405·000	15·2591	0·000203
Land use	Mg	5015·02	3	1671·67	1·47869	0·227179
Depth	Mg	11068·51	1	11068·51	9·79070	0·002498
Land use	B	0·034765	3	0·011588	3·257	0·026204
Depth	B	0·254251	1	0·254251	71·458	0·000000
Land use	Cu	1554·48	3	518·160	2·208865	0·094028
Depth	Cu	382·81	1	382·812	1·631893	0·205382
Land use	Fe	9090·2	3	3030·1	2·0443	0·114875
Depth	Fe	97092·1	1	97092·1	65·5050	0·000000
Land use	Mn	832·94	3	277·648	1·95793	0·127574
Depth	Mn	3768·89	1	3768·885	26·57768	0·000002
Land use	Zn	3990·32	3	1330·105	1·990585	0·122617
Depth	Zn	1658·93	1	1658·931	2·482693	0·119314
Land use	Ph	1·578	3	0·526	13·25	0·000000
Depth	Ph	0·561	1	0·561	14·14	0·000334
Land use	CEC	11199·2	3	3733·1	4·6489	0·004915
Depth	CEC	59394·1	1	59394·1	73·9654	0·000000

Table IV. Results of *posthoc* analysis performed with Scheffé's test for revealing influence of land use on the content of organic matter

	F2	F1	Eucalyptus	Pasture
Forest F2		0·929965	0·004107	0·000411
Forest F1	n.s.		0·039985	0·006511
Eucalyptus	s.	s.		0·919953
Pasture	s.	s.	n.s.	
Mean content of organic matter	41·500	39·778	32·000	30·200

The catchments are classified into six levels according to the capacity of native forests to prevent sediment delivery per unit of area (Figure 3).

Land Use and Quality of Water

The significant correlations detected in the regression analysis between proportion of land use and chemical parameters of water are presented in Table II. The percentage of pasture in any of the three buffer zones considered, that is 30, 100 and 200 m, had significant correlation ($p < 0{\cdot}05$) with alkalinity in the summer and in the winter. Percentage of native forest in the three buffer zones had significant correlation ($p < 0{\cdot}05$) with alkalinity in the autumn. In the winter, significant correlations ($p < 0{\cdot}05$) were also found when buffer zones of 30 and 200 m were considered.

However, the low values of R^2 obtained in all these cases indicate that the regressions explain a low proportion of the variation in the alkalinity data. No significant correlation was detected when considering percentage of eucalyptus as the predictor variable, neither when considering any of the other chemical parameters as the response variable.

Soil Fertility

Results of ANOVA (Table III) indicate significant effect of land use on pH, CEC, mean organic matter content, potassium (K), calcium (Ca) and boron (B). The effect of depth is significant for all the chemical parameters, except copper (Cu).

Posthoc analysis using the Scheffé's test detected significant differences only in the contents of organic matter when native forests were compared with eucalyptus and with pastures (Table IV). No differences were found between eucalyptus and pastures, nor between the two types of native forest. Therefore, the land uses can be merged in two classes

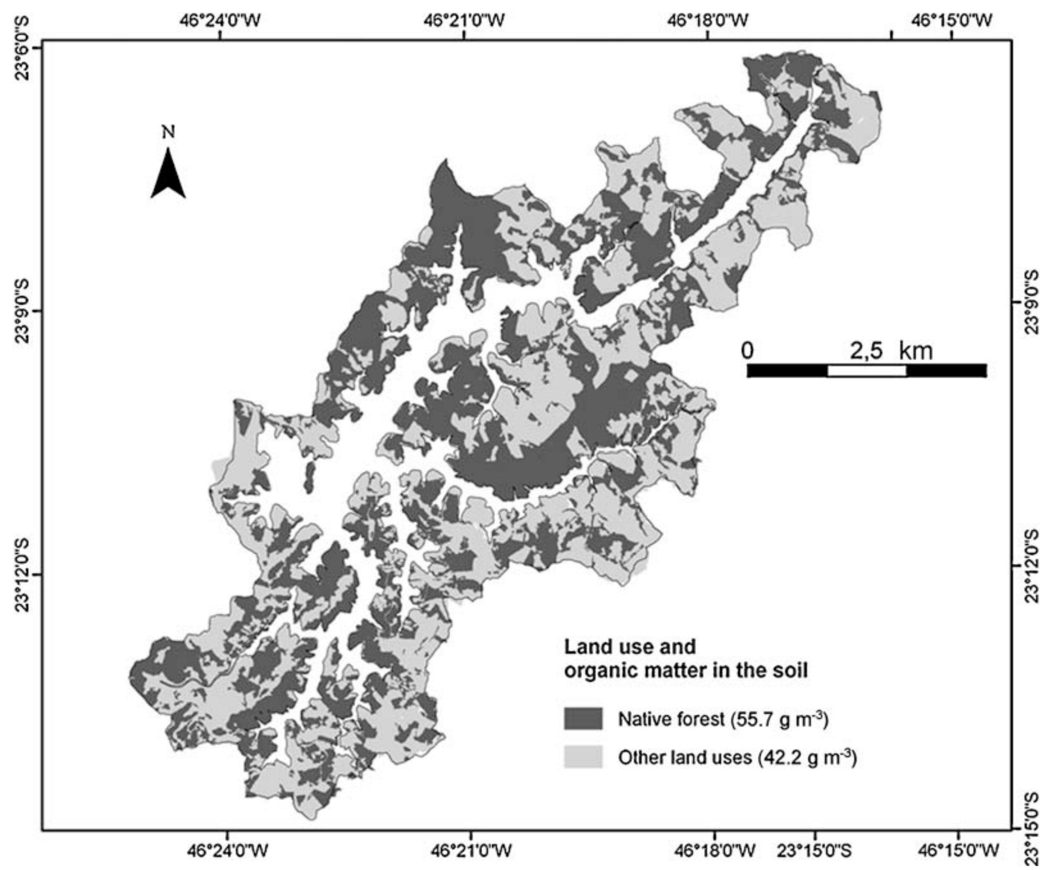

Figure 4. Mean contents of organic matter in soils occupied by native forests or other uses.

related to the content of organic matter: the lands with native forest and those without native forest. The mean contents of organic matter at the depth interval of 0–20 cm, calculated for these classes are 55·7 and 42·15 g dm^{-3}, respectively. Extrapolation of these classes of organic matter to the entire study area is illustrated in the map of Figure 4.

The Scheffé's test performed for all possible multiple comparisons of land uses for the remaining nutrients considered in this study revealed significant differences only in the content of Ca, when eucalyptus was compared with pasture ($p = 0{\cdot}006$), and in the content of B, when forest type F1 was compared with pasture ($p = 0{\cdot}0436$).

DISCUSSION AND CONCLUSION

Ideally, a remnant of pristine forest should be assessed in the study area in order to determine the maximum capacity of natural forests to contribute to mitigation of climate change. However, the Atlantic Forest biome has been severely disturbed by humans over the past 500 years (Dean, 1996) and no pristine forest is encountered in the region and it is therefore not possible to find a reference area to study carbon storage.

Both classes of native forest that have been studied, that is F1 and F2, are secondary and their biomass is probably still increasing. If these forests remain untouched in the future their average carbon stock above ground may be higher than the estimated 113·4 tons ha^{-1} for forests F2. In the west of São Paulo, for instance, the carbon stock estimated in another study in the same type of forest, although it was in another type of soil, was 149 tons ha^{-1} (Melo and Durigan, 2006). Although the maximum capacity of carbon storage is unknown, results of the current study revealed that even the younger native forests are more efficient than eucalyptus and pastures in their capacity to store carbon.

If the eucalyptus plantations remain untouched for a long time their stock of carbon will also probably increase and may achieve a value beyond that estimated by Paixão *et al.* (2006). However, considering the practices of eucalyptus plantation currently adopted in Nazaré Paulista, cycles longer than 6 years are not likely to occur.

The assessments of carbon in this study were focused on above ground biomass of trees whose trunk circumference is greater than 17 cm. Other carbon pools like soil, lianas and small trees have not been considered, thus the complete stocks of carbon were not determined. Nevertheless, the results obtained provide an initial understanding of the potential magnitude of the contribution of each land use for mitigation of climate change.

The map of land uses and carbon stocks in Figure 2 can be used as a tool to predict the consequences of interventions in the landscape. The maps indicate that restoration of 1 ha of native forest may alleviate climate change through storing more than 113 tons of carbon in forest biomass over the period of 30 years when the forest is expected to grow, whereas deforestation in 1 ha may intensify climate change by releasing to the atmosphere this amount of carbon.

The order in which the main types of land uses were considered to contribute to the mitigation of climate change (native forests, eucalyptus, pastures and bare soil) is the same as that for the services associated with the prevention of sediment delivery to the reservoir.

If the entire study area were occupied by native forests a total of 9 tons of sediment yield would be expected every year. However, occupation of the entire area by pasture would be more detrimental to the storage of water in the reservoir as the estimated amount of sediment delivered per year would be about 1500 tons. Effects of occupation of all the area by eucalyptus are closer to native forests with 36 tons of sediment yield per year. The estimated prevention of sediment yield in the current land use scenario is 1037 tons y^{-1}; therefore restoration of native forest in the study area has the potential to mitigate up to 500 tons of sediment delivery per year. The achievement of this optimum level of ecosystem service probably is not feasible because local forces such as the economic opportunity cost of nonforest land uses would impede the establishment of native forests in the entire area.

Forest recovery may be feasible in a certain proportion of the deforested lands, thus the classification of the 188 catchments of the study area according to the capacity of forests to prevent sedimentation is helpful for choosing the most appropriate areas to be restored. Despite most studies that have used the MUSLE approach for estimating the amount of sedimentation (Araujo-Junior, 1997; Chaves and Piau, 2006) being focused in single catchments the current research has demonstrated how this approach can be applied to analyze a portion of the landscape that is formed by numerous catchments. The results obtained, such as the map classifying the watersheds according to the contribution of land use in preventing sedimentation (Figure 3) can be applied more broadly for the purposes of landscape management through revealing priority areas for planning interventions that can mitigate losses of soil and subsequent sedimentation.

The map in Figure 3 can, in the same manner, be helpful in land use decisions because it shows catchments in the landscape of the study area where forest conservation, forest restoration and deforestation will most affect the water storage in the reservoir.

The analysis of water chemistry indicated weak association between land uses in the buffer zones of streams and the quality of water with the exception of alkalinity. Therefore, the only consequence of changes in land use that could be perceived in water is a variation in the capacity of neutralization of acids that originate from water pollution.

Table V. Estimates of ecosystem services in the entire study area in the current land use scenario (S1) and in scenarios of maximum expansion of pastures (S2), eucalyptus (S3), native forests (S4) and bare soil/urban areas (S5)

Ecosystem services	Measurements	Current scenario (S1)	100% pastures (S2)	100% eucalyptus (S3)	100% native forests (S4)	100% bare soil/urban areas (S5)
Maintenance of soil fertility	Tons of organic matter in the soil at depth interval of 0–20 cm	737 744t	642 703t	642 703 t	849 314 t	642 703 t
Mitigation of sediment delivery into reservoir	Kilogram of soil delivered in the reservoir	227 076 kg	1483 kg	67 kg	9 kg	244 520 kg
Carbon sequestration	Tons of C	380 984	0	150 957	864 596	0

The independence of levels of nutrients such as phosphates, nitrite and nitrate, from the influence of land use is probably due to the current economic land use activities in the region: local farmers normally do not use mineral fertilizers; hence no meaningful leaching in water bodies can be expected.

Despite this lack of influence in the chemical quality of water, variations in land use were significantly related to some of the chemical parameters of soil fertility. The map in Figure 4 indicates that the mean content of organic matter is $55{\cdot}7\ g\,dm^{-3}$ in soils occupied by forests and $42{\cdot}15\ g\,dm^{-3}$ in other land uses. The difference, that is $13{\cdot}55\ g\,dm^{-3}$, can be interpreted as the rate of organic matter losses that may occur through conversion of forests, or the gains that may occur through restoration.

The results discussed above are helpful in quantifying in physical terms some of the negative impacts of land use change on human welfare. The maps in Figures 2,3 and 4 indicate, at the whole landscape, variations in: the amount of carbon potentially sequestered from the atmosphere, the amount of sediment delivered to the reservoir, and the amount of organic matter retained in the soils if native forests are replaced or if they replace other land uses.

Results of this study also reveal the maximum and the minimum achievable values of ecosystem services in the study area according to extreme expansion of the current main land uses (Table V).

Gains of ecosystem services due to expansion of native forests in the entire area would be equivalent to 483 612 tons of carbon sequestered, 111 570 tons of organic matter maintained in the soil and 227 tons of sedimentation prevented per year. Losses of these services due to expansion of bare soil or urban areas would be equivalent to 380 984, 95 041 and 17 tons, respectively.

These results can support formulation of policies that aim to maximize benefits to humans from land use decisions. Among several potential strategies to be considered in such policies is economic valuation of ecosystem services followed by the development of mechanisms of payments for such services. For instance, financial resources originating from the marketing of carbon or from policies related to charging for the use of water could be used to compensate farmers that decide to conserve or to restore native forests in areas that are relevant for the provision of these ecosystem services. Furthermore, the results can be used by local authorities and decision makers for assessing the effectiveness of current policies in ensuring the capacity of the Atibainha Reservoir for storing water for human consumption.

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APPENDIX A

Sediment delivery rates ($kg\,ha\,y^{-1}$) for the different catchments with forests (PSDf), eucalyptys (PSDe), pastures (PSDp) and current land uses (CurS)

Catch	PSDf ($kg\,ha^{-1}$)	PSDe ($kg\,ha^{-1}$)	PSDp ($kg\,ha^{-1}$)	CurS (kg)	Catch	PSDf	PSDe	PSDp	CurS	Catch	PSDf	PSDe	PSDp	CurS	Catch	PSDf	PSDe	PSDp	CurS
0	8767	8766	8726	208 273	47	29 305	29 300	29 167	559 029	94	7748	7745	7678	303 762	141	31 904	31 898	31 753	916 965
1	4179	4179	4160	66 275	48	11 713	11 711	11 657	440 227	95	38 446	38 431	38 102	343 058	142	69 100	69 089	68 773	1 373 191
2	8108	8106	8069	73 149	49	80 270	80 256	79 890	2 291 335	96	34 181	34 176	34 036	1 098 947	143	48 639	48 631	48 409	1 460 584
3	15 408	15 406	15 335	566 883	50	11 709	11 707	11 654	428 467	97	12 449	12 443	12 325	327 279	144	55 247	55 238	54 985	621 752
4	9288	9286	9244	130 989	51	21 582	21 578	21 480	1 275 486	98	57 319	57 297	56 808	599 255	145	112 605	112 587	112 072	2 394 168
5	10 136	10 134	10 088	906 763	52	9534	9532	9489	350 050	99	37 068	37 051	36 700	193 711	146	16 634	16 631	16 555	1 460 263
6	11 129	11 128	11 077	511 937	53	10 614	10 613	10 564	244 935	100	12 900	12 895	12 785	304 055	147	20 086	20 082	19 991	1 232 652
7	6539	6538	6508	174 994	54	34 689	34 683	34 525	959 430	101	58 955	58 945	58 676	3 631 641	148	42 236	42 229	42 036	1 085 510
8	17 724	17 721	17 640	1 226 452	55	21 687	21 684	21 585	645 688	102	22 205	22 195	21 984	1 386 224	149	206 896	206 862	205 916	8 117 177
9	16 511	16 508	16 433	1 250 526	56	28 175	28 170	28 042	2 311 306	103	12 431	12 429	12 372	459 994	150	21 058	21 055	20 958	899 029
10	30 674	30 669	30 529	874 372	57	33 544	33 539	33 385	617 680	104	23 477	23 473	23 377	1 135 714	151	19 196	19 193	19 105	235 842
11	14 591	14 589	14 522	1 435 228	58	24 297	24 293	24 182	1 071 996	105	4494	4492	4454	163 642	152	71 941	71 929	71 600	3 269 256
12	26 167	26 162	26 043	351 151	59	30 287	30 282	30 144	702 854	106	15 464	15 462	15 399	476 532	153	25 936	25 931	25 813	386 235
13	7713	7712	7676	748 838	60	17 453	17 450	17 371	393 851	107	32 897	32 884	32 603	358 231	154	19 896	19 887	19 698	463 017
14	25 366	25 362	25 246	725 841	61	42 431	42 424	42 230	516 396	108	27 928	27 924	27 809	1 664 511	155	40 977	40 970	40 783	2 071 359
15	2938	2937	2924	28 867	62	13 971	13 968	13 904	140 445	109	22 408	22 398	22 185	1 039 644	156	30 137	30 132	29 994	1 008 275
16	12 696	12 693	12 635	265 716	63	6310	6309	6283	556 565	110	26 847	26 835	26 580	1 859 585	157	71 449	71 437	71 111	1 801 008
17	5658	5657	5631	150 488	64	24 488	24 484	24 372	706 568	111	30 741	30 736	30 596	391 961	158	35 711	35 705	35 542	1 898 561
18	12 523	12 521	12 464	126 860	65	19 059	19 055	18 968	437 442	112	16 409	16 406	16 339	245 345	159	55 571	55 561	55 307	2 882 588
19	7968	7967	7931	211 468	66	7090	7087	7019	73 617	113	42 909	42 890	42 483	3 254 406	160	70 262	70 251	69 930	3 681 968
20	13 290	13 288	13 227	161 221	67	3431	3430	3416	59 282	114	46 678	46 671	46 457	1 914 297	161	16 578	16 575	16 500	409 678
21	56 276	56 267	56 009	2 404 464	68	31 425	31 420	31 276	519 240	115	13 947	13 945	13 881	701 557	162	5989	5988	5964	179 416
22	13 377	13 374	13 313	272 507	69	19 934	19 931	19 840	348 993	116	10 214	10 212	10 165	107 928	163	44 978	44 970	44 765	1 630 524
23	13 702	13 700	13 638	358 287	70	142 267	142 202	140 854	5 934 699	117	26 765	26 761	26 651	1 187 050	164	37 155	37 138	36 785	829 987
24	51 029	51 020	50 787	529 658	71	2817	2816	2792	34 246	118	75 301	75 267	74 553	2 707 464	165	72 295	72 283	71 953	728 042
25	82 030	82 016	81 641	2 763 272	72	6176	6175	6147	74 152	119	18 564	18 561	18 476	656 636	166	3266	3266	3252	19 793
26	15 474	15 472	15 401	453 028	73	8101	8100	8067	371 571	120	33 568	33 553	33 235	336 067	167	8806	8804	8768	251 879
27	11 973	11 971	11 916	106 161	74	14 321	14 319	14 253	443 832	121	95 109	95 093	94 659	1 224 448	168	79 695	79 658	78 903	4 501 292
28	43 556	43 548	43 349	856 956	75	86 198	86 158	85 341	720 086	122	17 210	17 207	17 136	878 527	169	103 755	103 738	103 263	5 474 280
29	34 090	34 084	33 929	420 942	76	3124	3124	3111	36 209	123	10 149	10 147	10 101	255 456	170	88 006	87 966	87 131	3 639 468
30	10 210	10 208	10 162	289 643	77	92 964	92 922	92 040	2 443 153	124	5864	5863	5836	70 461	171	45 535	45 527	45 319	3 339 423
31	51 959	51 951	51 713	1 126 040	78	6479	6478	6452	1 206 392	125	84 128	84 114	83 730	1 359 012	172	47 483	47 476	47 259	6 035 209
32	8641	8639	8600	236 979	79	21 652	21 642	21 436	992 099	126	32 624	32 618	32 469	611 952	173	7775	7772	7705	450 861
33	39 695	39 688	39 507	1 633 637	80	40 739	40 732	40 546	729 801	127	16 645	16 642	16 566	2 778 871	174	5800	5799	5775	320 940
34	12 913	12 910	12 851	288 077	81	13 385	13 383	13 322	216 844	128	5359	5358	5334	125 200	175	8693	8690	8616	88 877
35	44 621	44 614	44 410	2 834 828	82	28 720	28 706	28 434	1 210 361	129	9670	9668	9624	118 725	176	77 774	77 739	77 002	10 648 759
36	12 011	12 009	11 954	489 100	83	6202	6201	6175	572 231	130	10 726	10 725	10 676	313 453	177	48 414	48 406	48 185	8 623 722
37	18 009	18 006	17 924	567 749	84	38 773	38 766	38 589	2 198 742	131	17 105	17 102	17 024	481 798	178	8466	8465	8430	321 482
38	35 810	35 804	35 640	623 122	85	40 360	40 344	39 999	825 071	132	71 891	71 879	71 551	2 965 029	179	150 110	150 041	148 618	4 395 161
39	180 123	180 094	179 271	4 882 046	86	101 382	101 335	100 374	3 143 296	133	15 725	15 723	15 651	2 171 329	180	16 656	16 650	16 507	395 597
40	17 015	17 012	16 934	731 331	87	43 889	43 883	43 703	1 677 835	134	21 169	21 165	21 068	419 725	181	8909	8908	8871	786 555
41	61 050	61 040	60 761	1 889 538	88	30 165	30 151	29 866	316 488	135	17 238	17 235	17 156	1 280 388	182	76 529	76 516	76 167	1 419 475
42	14 737	14 734	14 667	414 932	89	30 132	30 127	29 989	156 195	136	10 326	10 324	10 277	314 141	183	79 180	79 167	78 805	941 708
43	52 419	52 410	52 170	1 701 623	90	8081	8080	8047	415 613	137	55 506	55 497	55 243	1 008 430	184	7375	7374	7343	235 165
44	19 740	19 736	19 646	465 165	91	6787	6784	6726	344 182	138	9713	9711	9667	173 986	185	81 675	81 637	80 863	2 024 527
45	61 209	61 199	60 919	2 220 190	92	36 789	36 775	36 460	1 126 450	139	33 548	33 542	33 389	439 095	186	60 471	60 461	60 185	4 112 507
46	68 228	68 216	67 905	1 258 485	93	7369	7368	7337	90 237	140	59 762	59 752	59 479	2 314 909	187	17 727	17 724	17 643	913 888