Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **26**, 63–76 (2001)

EFFECTS OF HISTORICAL LAND USE ON SEDIMENT YIELD FROM A LACUSTRINE WATERSHED IN CENTRAL CHILE

MARCO CISTERNAS*, ALBERTO ARANEDA, PATRICIA MARTÍNEZ AND SERGIO PÉREZ
Centro EULA-Chile, Universidad de Concepción, Chile

Received 28 September 1999; Revised 30 May 2000; Accepted 24 July 2000

ABSTRACT

Sediment yield in the San Pedro Lake watershed, inferred from sedimentation in the lake, can be related to land use changes shown on aerial photographs taken during the period 1943–1994. In this watershed, which covers 4·5 km^2 of mountainous terrain in San Pedro County, central Chile, the area of native forest species decreased from 70 per cent in 1943 to 13 per cent in 1994. During this same period, the area of pine plantations increased from 4 to 46 per cent. To study effects of these changes, we took a core from the centre of the lake and estimated sedimentation rates by ^{210}Pb dating, which we checked with ^{137}Cs and pine pollen. The results show that sedimentation rate ranged from 5 mg cm^{-2} a^{-1} in the late 1800s to 60 mg cm^{-2} a^{-1} in the late 1960s. These rates, together with assumptions about the production and delivery of the sediment, give corresponding figures for sediment yields with maximum values close to 1 t ha^{-1} a^{-1}. Sediment yield between 1955 and 1994 closely tracks the total land use change that can be detected, irrespective of land use type, on sets of aerial photographs taken four to 18 years apart. However, this measure of land use change, while convenient and successful as a predictor of historical erosion, may be unreliable because it probably excludes many changes that occurred in long intervals between successive photographs. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: lake sediments; sediment dating; sediment yield; land use; GIS; Chile

INTRODUCTION

In the history of environmental disturbance by people, the greatest impact has been made over the last two centuries. The technical and industrial revolution has significantly disturbed the planet, not only its ecosystems but also its soils, streams and lakes. Nevertheless, most environmental studies are concerned with ongoing damage. This approach has a limited perspective since it provides only one snapshot of a system that has a time scale of hundreds of years of human disturbance and thousands of years of natural post-glacial change.

Over the last decade, physical geographers and environmental researches have valued the role of lake sediments as 'historical recorders' of environmental change (Dearing, 1991; Smol, 1992; Boer, 1994; Dixit *et al.*, 1995; Millspaugh and Whitlock, 1995; Auer *et al.*, 1996; Spliethoff and Hemond, 1996; Van der Post *et al.*, 1997). Slowly deposited lacustrine sediments can record both natural, baseline conditions and subsequent human disturbance.

In studies that use the sediments of a lake to gauge human disturbance in the surrounding watershed, the ^{210}Pb isotope is commonly employed for estimating the sedimentation rate in the lake, which in turn provides an estimate of the sediment yield from the watershed (Battarbee *et al.*, 1985; Dearing, 1991; Appleby and Oldfield, 1992; Boer, 1994; Van der Post *et al.*, 1997). In this paper we quantify the sediment yield in a small disturbed lacustrine watershed by dating lake-bottom deposits with ^{210}Pb. We check the dates with ^{137}Cs derived from atomic-bomb testing that peaked and ended in 1963, and with pollen from pine trees introduced in the 1880s. We find that changes in sediment yield correlate with a simple but imperfect measure of land use change detected on air photos from the past 50 years.

* Correspondence to: M. Cisternas, Centro EULA-Chile, Universidad de Concepción, Casilla 160-C, Concepción, Chile
Contract/grant sponsor: FONDECYT; contract/grant number: 1980529
Contract/grant sponsor: DIUC; contract/grant number: 96.310.021-1.1

STUDY AREA

Chica de San Pedro Lake (36°51′S, 73°05′W) is located in San Pedro County, central Chile, beside the Biobío floodplain close to the Pacific Ocean (Figure 1). The lake is bordered by mountains composed of metamorphic rocks except to the northwest, where the lake is impounded by fluvial sediments of basaltic composition (Aguirre *et al.*, 1972). The drainage basin of the lake covers 4·5 km^2. The lake has a surface area of 0·87 km^2, a maximum depth of 18 m and an average depth of 10·3 m (Parra *et al.*, 1976; Parra 1989).

The floor of Chica de San Pedro Lake has steep slopes on its west, south and east sides (Figure 1). The northern side is less abrupt. The central part of the lake floor is nearly flat. These bathymetric characteristics reflect the geomorphological evolution of the lake: soon after the last glaciation, a ravine was blocked by sediment of the Biobío River, and the resulting lake has been largely filled, in Holocene time, with sediments derived from Chica de San Pedro watershed (Cisternas *et al.*, 1997).

Many historical human activities have affected the lake and its watershed: clear-cutting of the native forest, raising of wheat, introduction of exotic trees, and urbanization (Cisternas *et al.*, 1999). In the past 50 years, some of this land use has been influenced by economic policies of the Chilean government. Replacement of native forest by pine plantations, which began in the late 1800s, accelerated in the 1930s under a national economic policy to develop the forestry in central Chile (Morales, 1989; Unda and Ravera, 1994). Such plantations, many of which replaced native forests soon after the native trees were logged, were established without special preparation of the soils or slopes (Morales, 1989).

The time of these changes includes the time recorded by our core (see results below and Figure 2) and the period of record for precipitation in nearby San Pedro County (Figure 3A). In the past 50 years, the annual precipitation was in the ranged of 1–2 m a^{-1} and averaged 1·55 m a^{-1}. The annual precipitation fluctuated throughout this time without overall trends longer than a few years.

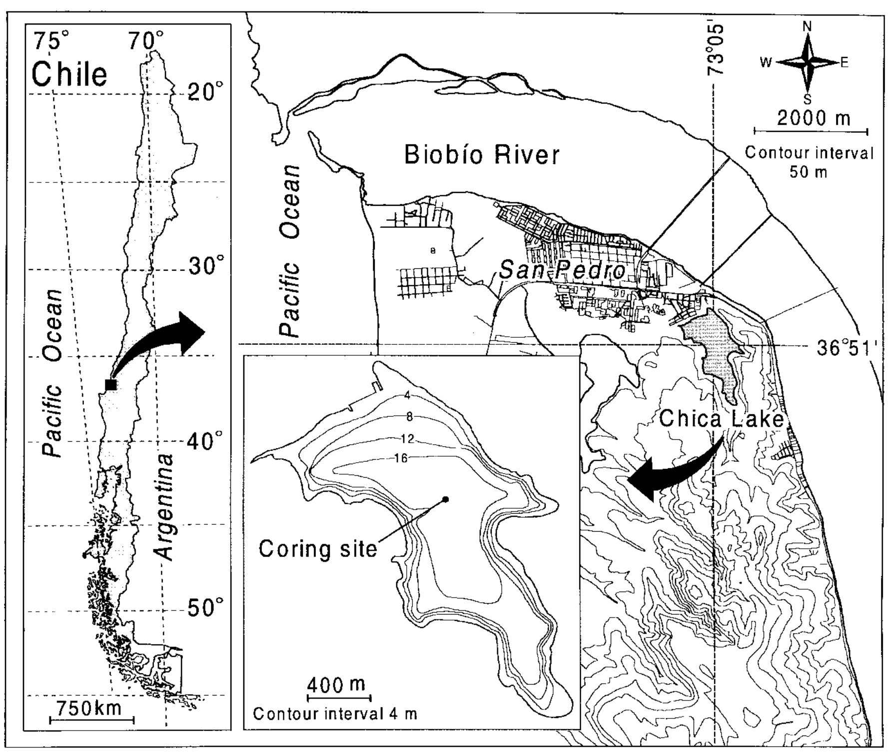

Figure 1. Location of study area, bathymetric map and coring site

METHODS

Sampling and laboratory analysis

A core sample 50 cm long and 6 cm in diameter was obtained in 1996 by scuba diving from the central and deepest part of the Chica de San Pedro Lake (Figure 1). First, the core was X-rayed to check for biological or physical disturbance, a lack of which simplifies the isotope and pollen analysis. Then, the core was extruded vertically and cut into 1 cm slices. Each such slice was analysed, by standard methods, for dry density (drying at 105 °C) and organic carbon (loss on ignition at 550 °C).

The ^{210}Pb (half-life: 22·3 years) activity of each slice was calculated from the measured activity of its first daughter isotope, ^{210}Po (half-life: 138·4 days), by means of alpha spectrometry (Hasanen, 1977). Supported ^{210}Pb (the amount in equilibrium with radium in the sediment matrix) was estimated from the ^{210}Po activity of the three lowest slices; these slices showed nearly identical activities.

To check the ^{210}Pb dates, the samples were also analysed for ^{137}Cs. Atmospheric testing of nuclear weapons in the 1950s and early 1960s produced this isotope, which has a half-life of 32 years. It reached its maximum atmospheric activity in 1963, just before signing of the test-ban treaty (Wan *et al.*, 1987; Robbins *et al.*, 1990). To measure ^{137}Cs that became incorporated in the samples, we used a gamma-ray spectrometer with a solid state Ge(Li) detector (Piñones and Tomicic, 1995).

Pine pollen was analysed to provide a further check on the ^{210}Pb chronology. Chile lacked pine trees until *Pinus radiata D. Don* was introduced there near the close of the 19th century. In San Pedro County, a coal mining company began widespread planting of *P. radiata* in 1885 (Aztorquiza, 1929; Contesse, 1987; Millán and Carrasco, 1993; Donoso and Lara, 1996). Later, in the 1930s, the plantations were spread further, throughout south-central Chile, as a policy of the national government (Contesse, 1987). Because this history makes pine pollen at Chica de San Pedro Lake no older than the 1880s, the lake's deposits of about that age should contain the deepest *P. radiata* pollen. Accordingly, we looked for pine pollen in 1 g of dry sediment from each slice of the core. To separate the pollen from the sediment matrix we used standard palynological techniques (Faegri and Iversen, 1975; Dupré, 1992), and to measure concentrations of the pollen, in grains per gram, we used the methods of Anderson (1974) and Kempt *et al.* (1974).

Calculation of sedimentation rates and sediment yield

Ages and sedimentation rates were determined from ^{210}Pb activity by means of the CRS (Constant Rate of Supply) model. In this model, the supply of ^{210}Pb from the atmosphere does not vary with time (Goldberg, 1963; Appleby and Oldfield, 1978, 1992).

To estimate sediment yield from the watershed, we considered a method proposed by Dearing (Dearing *et al.*, 1987; Dearing, 1991). In its simplest form, this method is based on three assumptions that are not necessarily valid for Chica de San Pedro Lake: (1) the sedimentation rate does not vary with location in the lake; (2) all the sediment supplied by the watershed is deposited in the lake, no sediment is stored in transit; (3) all the sediment deposited in the lake, organic as well as inorganic, comes from in the watershed, none of the sediment is produced within the lake itself.

We applied this method in two ways: with and without a correction intended to obviate assumption (3). To make the correction, we subtracted the organic fraction measured by loss on ignition, to obtain the yield of inorganic sediment only. We also calculated a total sediment yield that includes organic sediment, whatever its source.

Measurement of land use changes

San Pedro watershed land use patterns were determined from aerial photographs taken in 1943, 1955, 1961, 1978, 1981 and 1994. To outline the watershed on the photographs, we used topographic maps with a scale of 1:10 000 and a contour interval of 10 m that we adjusted to the photograph scales. Then, using the six sets of aerial photographs, we mapped six categories of land use: native forest, bushes, deforested areas, exotic forest (pine plantation), urban-residential and grassland.

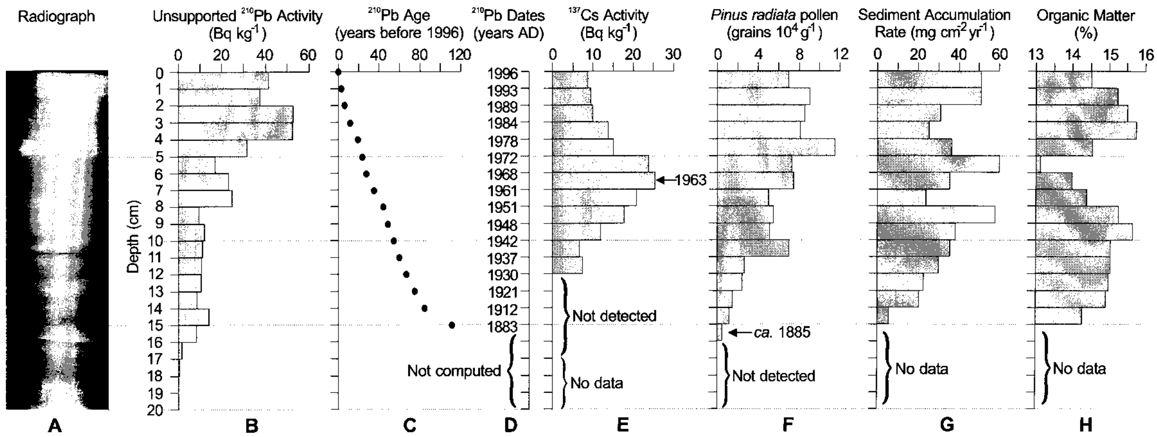

Figure 2. Radiograph, unsupported ^{210}Pb activity, chronological model, ^{137}Cs activity, *Pinus radiata* concentration, sediment accumulation rate and organic matter plotted against depth in the Chica de San Pedro Lake core

Using ARC/INFO GIS software, we measured areas of these land uses, adjusted to take account of land slope. To calculate slope we used the mapped topography to construct a digital elevation model (DEM), from which a digital terrain model (DTM) was derived. The DTM allowed us to increase previously calculated land use areas in proportion to the slope. These methods yielded percentages, for each of the six sets of aerial photographs, of area covered by each land use type.

Changes in land use were detected by comparing consecutive photographs. To summarize changes we used ARC/INFO to compute a quantity we call the total detectable change. This computed value, expressed as a percentage of the watershed area, denotes the total land use change without regard for the kind of change (such as a change from native forest to exotic forest). We also computed the rate of total detectable change by dividing the total detectable change by the amount of time between successive photographs.

These total changes are merely 'detected' because each was computed by comparing photographs that show conditions at the beginning and end of a period of time. Such photographs do not necessarily show all the land use changes that took place in this measurement period. As a result, we unavoidably failed to detect many of the land use changes that have occurred in the watershed of Chica de San Pedro Lake between 1943 and 1994.

RESULTS

Radiography

Radiography shows the core suitable for measurement of sedimentation rates. As shown in Figure 2A, the core lacks obvious signs of burrowing, or other disruption, that could have redistributed ^{210}Pb, ^{137}Cs or pollen after their deposition. Instead, the entire core contains horizontal strata a few millimetres to about 2 cm thick.

^{210}Pb isotope flux

The total residual unsupported ^{210}Pb load in the core is 0·07569 Bq cm^{-2}. This load implies a ^{210}Pb flux rate of 23·57 Bq m^{-2} a^{-1}; this flux rate is lower than normally found in the northern hemisphere, as discussed below.

Unsupported ^{210}Pb activity and chronological model

In a simple case, where both ^{210}Pb fallout and sedimentation rate are constant through time, the ^{210}Pb activity in a core declines smoothly with depth from a maximum at the top to a constant value – the supported ^{210}Pb activity – in equilibrium with radium in the sediments (Goldberg, 1963; Appleby and Oldfield, 1978). Under these simple conditions, the downward decrease in unsupported ^{210}Pb activity is controlled solely by the age of the deposit, which controls progressive decay of the ^{210}Pb that had accumulated as fallout.

In our core, unsupported ^{210}Pb activity shows an overall decrease downward (Figure 2B). Interpreted with the CRS model, in which ^{210}Pb fallout does not change with time (see Methods), this trend implies that the top 15 cm of the core spans a little more than a century (Figures 2C and D). The earliest date inferred from this model, for deposits 15 cm below the surface, is 1883. For the top of the core, we fit the model to a date of 1996–the year the core was taken–and we compute intermediate dates at 1 cm intervals. This series of dates is mostly consistent with ^{137}Cs and pollen data in Figure 2E and F, as discussed below.

The unsupported ^{210}Pb profile contains several fluctuations that are superimposed on the overall downward decrease in activity (Figure 2B). If ^{210}Pb fallout is assumed constant, these fluctuations imply relative changes of sedimentation rate (Figure 2G). The relative minima in ^{210}Pb activity imply relative maxima in sedimentation rate because, if constant ^{210}Pb fallout produces a constant ^{210}Pb flux to the lake bottom, rapid sedimentation dilutes the ^{210}Pb activity (Battarbee *et al.*, 1985; Dearing 1991; Olavi *et al.*, 1990; Alvisi and Frignani, 1996). The highest peak is defined by unsupported activity that is highest not at the top of the core but at a depth of several centimetres. Additional peaks are present lower in the sequence.

^{137}Cs and pollen tests of the ^{210}Pb chronology

The profile of ^{137}Cs activity is dominated by a broad peak that agrees exactly with dates inferred from ^{210}Pb (Figure 2E). The likely date of this peak is 1963, when ^{137}Cs reached its maximum in the atmosphere. The peak corresponds to the time between 1961 and 1968 in the ^{210}Pb chronology. The activity declines above 6 cm depth in the core, probably because almost no ^{137}Cs has been added to the atmosphere since signing of the test-ban treaty in 1963.

The lower part of the ^{137}Cs profile, however, conflicts with the ^{210}Pb chronology. ^{137}Cs remains detectable to depths corresponding to ^{210}Pb dates in the 1930s. These ^{210}Pb dates may be about 20 years too old, for atmospheric testing of nuclear weapons produced little ^{137}Cs before the early 1950s. Alternatively, ^{137}Cs migrated several centimetres downward by diffusion after deposition. Diffusion may have also spread the peak that we assign to 1963, but it probably did not move that maximum upward or downward.

Despite discordance between ^{210}Pb dates and the lowest part of the ^{137}Cs profile, earlier dates in the ^{210}Pb chronology are consistent with the lowest appearance of *P. radiata* pollen (Figure 2F). This lowest pollen, at a depth of 15–16 cm, may have come from the trees introduced in 1885. If so, the pollen data support the ^{210}Pb date of 1883 that we computed for a depth of 15 cm.

Sedimentation rates

According with the CRS model, net sediment accumulation has varied by an order of magnitude, from 5 mg cm^{-2} a^{-1} in 1883 to 60 mg cm^{-2} a^{-1} in 1968 (Figure 2G). Changes in sedimentation rates show three pulses of sedimentation in the 20th century. The first began late in the 19th century and reached its maximum in the late 1940s (58 mg cm^{-2} a^{-1}). Another pulse began early in the 1950s (24 mg cm^{-2} a^{-1}) and reached its maximum in the late 1960s (60 mg cm^{-2} a^{-1}). The most recent event started around 1978 (26 mg cm^{-2} a^{-1}) and continued into the 1990s, when the maximum was 52 mg cm^{-2} a^{-1}.

The deposition of 15 cm of sediment between the computed date of 1883 and the core-top date of 1996 gives a mean sedimentation rate of 1·33 mm a^{-1}. Because the measured mass of sediment is equivalent to 3·35 g for a column 15 cm tall and 1 cm^2 in horizontal cross-section, the corresponding mass accumulation rate averages close to 30 mg cm^{-2} a^{-1}.

Organic content

All these figures refer to the sum of inorganic and organic sediment. By measuring loss on ignition, we found that organic content varies little with depth – from 13 to 16 per cent of dry weight in the top 15 cm of the core (Figure 2H). The minimum organic content of 13 per cent corresponds to a model age of 1968.

We converted organic content to organic sedimentation rate by applying the obtained age-sedimentation model. The results show that the organic sedimentation rate was nearly constant for the model years 1942–1996 (Figure 3B, diagonal hatching).

Some of the organic matter probably came from the watershed, while other organic material was probably produced within the lake, but the proportions that can be assigned to these sources are unknown. For these reason, we emphasize the inorganic component of the sediment yield from the watershed.

Sediment yield

We computed watershed sediment yield as $S^{*}A_{L}/A_{W}$, where S is the sedimentation rate at the core site, A_{L} the area of the entire lake bed, and A_{W} the watershed area corrected for land slope. This simplified approach, from Dearing *et al.* (1987) and Dearing (1991), depends on three assumptions stated in the Methods section. We made the computations for the top 10 cm of the core, which according to our ^{210}Pb dating corresponds to the time between 1942 and 1996. This period contains the years of all the aerial photographs with which we measured changes in land use.

Sediment accumulation rate and sediment yield, both plotted on a linear time scale, retain the same three pulses recognized in the depth plot (Figure 2G) but show that they were brief (Figure 3B). The first two peaks, around 1950 and 1970, lasted several years; the third peak, in the 1990s, about seven years. All three approached 1 t ha^{-1} a^{-1}. Values below the mean yield (0·5 t ha^{-1} a^{-1}) prevailed for longer periods of time.

Organic matter, whatever its origin, has little effect on these patterns. Because the accumulation rate of organic matter varies little with time, organic matter merely increases the total sediment yield by a value that is relatively small (0·1–0·2 t ha^{-1} a^{-1}) and nearly constant (Figure 3B). Consequently, the potential production of organic matter within the lake creates little uncertainty about sediment yield from the watershed.

Land use changes

The watershed of Chica de San Pedro Lake is dominated by a ravine that drains directly into the lake (Figure 3C). The steepest and highest areas are located in the southern headwaters. Because of topographic relief, the watershed area calculated with the DTM (4·8 km^{2}) is 7 per cent greater than the planar area.

Most of the native forest in the watershed has disappeared in the past 50 years (Table I). In 1943, the date of our earliest air photos, native forest covered 70 per cent of the area, mainly in the south-central part of the watershed. This land use shrank to 13 per cent by 1994. Concurrently, pine plantations expanded from 4 per cent in 1943 to 46 per cent in 1994. Because these plantations have progressively replaced native forest, the watershed was never completely deforested in the past 50 years.

Land uses other than native and exotic forest show various tendencies. Between 1943 and 1994, heterogeneous bushes ranged from a minimum of 19 per cent in 1978 to a maximum of 30 per cent in 1955. Deforested areas, though lacking in 1943 and 1955, covered 16 per cent in 1961, 14 per cent in 1978, 22 per cent in 1981, and just 8 per cent in 1994. The area of grassland was 4–5 per cent in all surveyed years through 1978; thereafter, grassland covered just 1 per cent in 1981 and was absent altogether in 1994. The urban and residential land use began in 1961 (1 per cent) and reached a maximum of 6 per cent in 1981.

Land use change, mapped to include all the measured kinds of land use change (the total detectable change defined in the Methods section), migrated progressively southward in the steepest part of the watershed between 1943 and 1994 (Figure 3C and D). Most of this migration was due to the spread of pine plantations, that is, to the expansion of exotic forest described above (Table I).

The area of total detected change, when summed for the entire watershed and expressed as a percentage of the area of the watershed, ranges from 30 per cent for the comparison between 1943 and 1955 air photos, to 64 per cent for the comparison between 1981 and 1994 (arrows and dots in Figure 3E). The total detectable

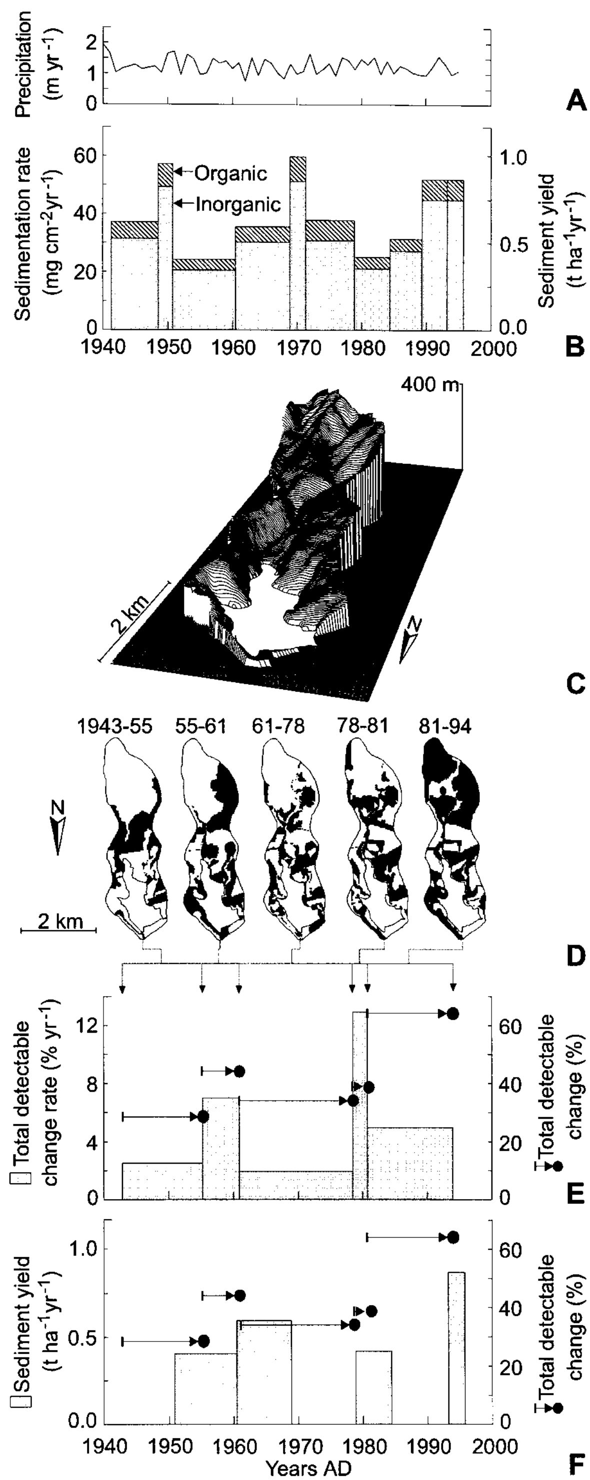

Figure 3. Precipitation record, sedimentation rate, sediment yield, DEM, total detectable change and total detectable change rate plotted against time

Table I. San Pedro watershed land-use percentages determined from aerial photographs taken in 1943, 1955, 1961, 1978, 1981 and 1994

Land use	1943	1955	1961	1978	1981	1994
Native forest	70·1	52·8	33·9	34·4	28·8	12·6
Bushes	21·6	30·2	24·8	18·7	28·5	28·5
Deforested areas	0·0	0·0	15·7	14·1	21·7	8·1
Exotic forest	4·4	12·3	19·8	22·6	13·6	45·7
Urban-residential	0·0	0·0	1·3	4·9	6·1	5·1
Grassland	3·9	4·7	4·4	5·3	1·2	0·0

change fluctuated between 30 and 40 per cent for the intervening comparisons (1955 and 1961, 1961 and 1978, 1978 and 1981).

As noted above (see Methods), these percentages probably exclude many land use changes that took place during the years between photographs. Such undetected changes probably explain the inverse relation between the rate of total detectable change (bars in Figure 3E) and the length of time between successive air photos. The lowest rate (2·5 per cent a^{-1}) was obtained from air photos taken 17 years apart, while the highest rate (13 per cent a^{-1}) comes from air photos just three years apart.

Relationships between sediment yield and land use

We looked for relationships between sediment yield inferred from the core and three kinds of land use measurements obtained from air photos (Figure 4). Only the last one, total detected change, shows a consistent relationship.

The estimated sediment yield appears unrelated to the first and most basic of our measures of land use – the percentage of the watershed covered by each of six types of land use (Table I). As shown in Figure 4A–F, we made a linear correlation analysis between sediment yield (from the sum of organic and inorganic rates; Figure 3B) and areal extent of different land uses (from the air photos taken in 1943, 1955, 1961, 1978, 1981 and 1994). Sediment yield may be related to land use in just two cases: it tends to increase with area of exotic forest (Figure 4D; $r^2 = 0{\cdot}44$) and to decrease with area of grassland (Figure 4F; $r^2 = 0{\cdot}36$). But the small sample size (five snapshots) makes even these trends statistically insignificant.

Estimated sediment yield has also no obvious correlation with the *rate* of total detected change – a rate normalized to the duration of the period between air photos (Figure 4G). The main cause of this non-correlation may be failure to detect land use changes that took place early in long periods between photographs. Such failure may explain why the average rate of total detected change varies inversely with the length of the period between photographs (as shown by the inverse relationship between the width and height of grey bars in Figure 3E). For example, average rates of detected change are lowest for the long intervals 1943–1955 and 1961–1978 (Figure 3E). The average rate is also low for the long interval 1981–1994, even though that time coincides with economic growth in Chile and immediately follows the period (1978–1981) having the highest average rate of detected change.

The estimated sediment yield apparently tracks total detected change in land use, but only if that change is expressed without regard for the length of time during which the change occurred. This somewhat surprising relationship is shown in Figure 3F, which compares sediment yield (sum of organic and inorganic rates selected from Figure 3B, replotted as grey bars) with the total detected change (from Figure 3E; arrows and dots). For graphic simplicity, the sediment yield data selected for Figure 3F represent only those four 1 cm core depth intervals that, according to our ^{210}Pb chronology, include the air photo years 1955, 1961, 1978, 1981 and 1994 (Figure 2D). The resulting comparison shows that sediment yield increases with the total detected change. This relationship gives an apparently high correlation ($R^2 = 0{\cdot}95$), but the sample size is

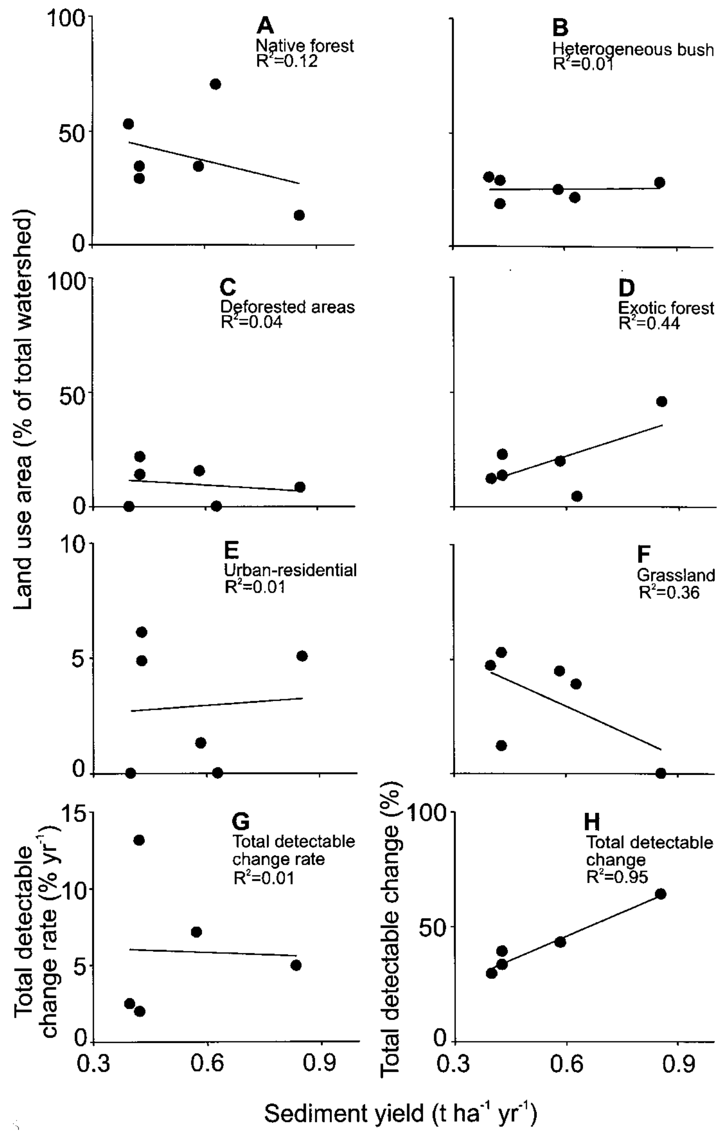

Figure 4. Linear correlation analyses between sediment yield and land-use change measures

small (Figure 4H). The reason for the apparently high correlation is unclear. We speculate that total detected change is dominated by changes that occurred late in each of the five periods between air photos. We further speculate that watershed sediment yield *c*. 1955, 1961, 1978, 1981 and 1994 responded mainly to these late changes.

IMPLICATIONS

Hemispheric control of ^{210}Pb flux in Chica de San Pedro Lake

Chica de San Pedro Lake shows much lower ^{210}Pb flux from the atmosphere than lakes in the northern hemisphere. Our results imply a flux close to 24 Bq m^{-2} a^{-1} near the coast of central Chile. By contrast, studies in the northern hemisphere have shown rates higher than 150 Bq m^{-2} a^{-1} (Preiss *et al.*, 1996).

Relative to the northern hemisphere, the low atmospheric flux of ^{210}Pb in Chica de San Pedro Lake may result from the low ratio of land to ocean in southern latitudes. Atmospheric ^{210}Pb is produced by decay of ^{222}Rn, and this in turn is produced by ^{226}Ra occurring in continental rocks (Appleby and Oldfield, 1992). For Chica de San Pedro Lake, and probably for other parts of western South America as well, the low ^{210}Pb flux may be limited by air masses from the Pacific Ocean. This maritime air, which produces precipitation in the region, probably carries less ^{210}Pb than air masses at northern latitudes, where continents cover more of the Earth's surface.

Sedimentation rates

The average sedimentation rate at Chica de San Pedro Lake (30 mg cm^{-2} a^{-1}) is higher than most of the rates reported from other South and Central American lakes where sedimentation rates have also been estimated from ^{210}Pb. Among eight such lakes, only two in Guatemala and one in Bolivia have yielded rates higher than 30 mg cm^{-2} a^{-1} (Binford, 1983; Binford and Brenner, 1986, 1989; Binford *et al.*, 1991; Brenner and Binford, 1988; Brenner *et al.*, 1990; Pourchet *et al.*, 1994,1995). The lowest of the reported rates is 9 mg cm^{-2} a^{-1} at Lake Titicaca and the highest is 75 mg cm^{-2} a^{-1} at Lake Kotia, both in Bolivia (Table II). Nevertheless, compared with some northern hemisphere lakes, Chica de San Pedro Lake has slow sedimentation (Table III). No such data are available from other Chilean lakes.

Sediment yield comparison with other watersheds

The watershed of San Pedro Lake resembles several European watersheds in the mean sediment yield estimated from lake deposits. As inferred above, the yield for the San Pedro watershed has a mean of 0·5 t ha^{-1} a^{-1} for the past 50 years. By comparison, in a small forested basin in south England, with a mean rainfall of 674 mm, erosion rate averaged 0·2 t ha^{-1} a^{-1} in the 20th century (Foster *et al*, 1985); around a Swedish lake, sediment yield increased from 0·05 t ha^{-1} a^{-1} under natural conditions to 0·5 t ha^{-1} a^{-1} in the 20th century (Gaillard *et al.*, 1991a); and at another Swedish lake, medieval deforestation increased the sediment yield from 0·25 to 0·86 and 2·5 t ha^{-1} a^{-1} (Dearing *et al.*, 1987).

The sediment yield around San Pedro Lake also resembles yields estimated from lake deposits in Mexico. There, erosion of the surrounding watershed accelerated before the Spaniards arrived: this acceleration was due to land use by the Chuipícaros and Purépechas; Europeans were not the first to degrade American soil (O'Hara *et al.*, 1993). The estimated sediment yield at this lake increased from 0·05 t ha^{-1} a^{-1} *c*. 3000 years ago to 0·13 t ha^{-1} a^{-1} *c*. 1600 years ago, further to its modern value of 0·36 t ha^{-1} a^{-1}.

Table II. Sedimentation rates reported from other South and Central American lakes where the rates have also been estimated from ^{210}Pb

Lake	Country	Mean sedimentation rate (mg cm^{-2} a^{-1})	Reference
Miragoane	Haití	11·0	Brenner and Binford, 1988
Chimaj	Guatemala	15·0	Brenner *et al.*, 1990
Chilonche	Guatemala	47·0	Brenner *et al.*, 1990
Quexil	Guatemala	16·0	Deevey et al., 1979
Yaxha	Guatemala	38·0	Deevey et al., 1979
Titicaca	Bolivia	28·0	Pourchet *et al.*, 1994
Titicaca	Bolivia	9·0	Binford *et al.*, 1991
Titicaca	Bolivia	10·7	Binford and Brenner, 1989
Kotia	Bolivia	75·0	Pourchet *et al.*, 1995
Jichhu kota	Bolivia	22·0	Pourchet *et al.*, 1995

Table III. Sedimentation rates reported from some northern hemisphere lakes where the rates have also been estimated from ^{210}Pb

Lake	Country	Mean sedimentation rate (mg cm^{-2} a^{-1})	Reference
Erie	USA, Canada	84·7	Kempt *et al.*, 1974
Huron	USA, Canada	15·7	Kempt *et al.*, 1974
Erne	Ireland	120·0	Olfield et al., 1978
Erne	Ireland	130·0	Olfield et al., 1978
Llyn Peris	England	270·0	Elner and Wood, 1980
Llyn Peris	England	280·0	Elner and Wood, 1980
Rostherne Mere	England	55·0	Elner and Wood, 1980
Rostherne Mere	England	52·0	Elner and Wood, 1980
Newton Mere	England	29·0	Elner and Wood, 1980
Mirwart	Belgium	140·0	Oldfield et al., 1980
Mirwart	Belgium	55·0	Oldfield et al., 1980
Mirwart	Belgium	120·0	Oldfield et al., 1980
Ontario	USA, Canada	45·2	Rowan et al., 1995
Blelham	England	190·0	Van der Post *et al.*, 1997

Our estimates further agree with yields obtained by a very different method applied to a very similar place: a watershed in a physical setting like that of San Pedro Lake, just 60 km to its southeast. For this watershed, erosion rates were deduced from topography, vegetation and precipitation with the Universal Soil Loss Equation (USLE; Oyarzún, 1997). The equation predicts yields of 0·25 t ha^{-1} a^{-1} for old-growth native forest, 0·52 t ha^{-1} a^{-1} for second-growth native forest, and 0·51 t ha^{-1} a^{-1} for pine plantations.

Validity of assumptions used in estimating sediment yield

These similarities with other watersheds show that our sediment yield estimates from San Pedro Lake, though just a first approximation, are probably about right. And even if the values are systematically wrong, their main temporal trends are probably real. There remain, however, questions about the assumptions on which the values are based.

According to our first assumption, the sedimentation rate does not vary with location in the lake. For lakes having broad, gently sloping shallows, sediment suspended by waves tends to be deposited preferentially in the central part of the lake (focusing effect); deposition is fastest where the water is deepest (Hilton, 1985; Hilton *et al.*, 1986; Evans, 1991). By contrast, Chica de San Pedro Lake has a broad, flat floor and narrow, steep sides (Figure 1). Such a shape tends to promote uniform deposition across the lake bottom (Blais and Kalff, 1995).

By the second assumption, all the sediment supplied by the watershed goes immediately into the lake. In reality, of course, the sediment may take various amounts of time to reach the lake. However, for the Chica de San Pedro watershed, two points suggest that the average delay is brief. First, the watershed has rugged topography (steep slopes, ravines, and mainly first-order streams; Figure 3C) that is likely to minimize delay from storage as alluvium. Second, the apparently high correlation between total detected change and estimated sediment yield (Figures 3F and 4H) implies an average delay of five or ten years at most (see Relationships between sediment yield and land use in Results section).

Additional findings show that our estimates of sediment yield contain little uncertainty from the third assumption–that all the sediment deposited in the lake, organic as well as inorganic, comes from the watershed, not from the lake (Dearing, 1991; Gaillard *et al.*, 1991b). First, as shown above (see Sediment yield in Results section), organic matter in Chica San Pedro Lake, though of largely unknown source, has little effect on estimated trends in sediment yield because the organic content is nearly constant (Figures 2H and 3B). Second, little of the inorganic fraction is likely to have originated in the lake, for biogenic silica makes up an average of 1·2 per cent (dry weight) of the top 15 cm of sediment in a core next to ours (Herrera, 2000).

Comparison between sediment yield and annual precipitation

The periods of highest sediment yield do not correspond with exceptional annual amounts of precipitation (Figure 3A and B). As described above, annual precipitation since 1940 has fluctuated between 1 and 2 m a^{-1} without increasing or decreasing for more than a few years. The graph of annual precipitation thus has many peaks without an overall trend (Figure 3A). All the maxima in sediment yield correspond with one or more of these peaks, but so do the minima.

This comparison is clouded by unavoidable differences in temporal resolution. Unlike the annual precipitation data in Figure 3A, the individual estimates for sediment yield span periods as long as ten years (Figure 3B).

Trends in sediment yield and land use

Like annual precipitation measured in San Pedro County, sediment yield estimated from our core shows no overall increase since 1940 (Figure 3A and B). This rather steady yield at first seems surprising because it occurred while the area of native forest declined drastically, from 70 to 13 per cent of the watershed between 1943 and 1994 (Table I).

The replacement of native forest by pine plantations may explain this surprising result. As noted in the Results section, prompt planting of pines limited the duration and extent of deforestation in the San Pedro Lake watershed. Such overall maintenance of forest cover may similarly explain the poor correlation between land use type and sediment yield (Figure 4A–F).

Nevertheless, land use changes detected on air photos do appear to have influenced sediment yield, as shown by its correlation with total detectable change (Figures 3F and 4H). Perhaps the controlling factor is change itself, rather than the kinds of land use beforehand and afterwards. There remains, however, the puzzle of how total detectable change predicts erosion so successfully without accounting for additional changes that probably took place in long intervals between air photos.

ACKNOWLEDGEMENTS

The authors are grateful to Michel Pourchet (Laboratoire de Glaciologie et Geophysique de l'Environnement, CNRS, France) for the ^{210}Pb analysis, to Igor Tomicic, Osvaldo Piñones, Humberto Oyarce (Comisión Chilena de Energía Nuclear) and Paulina Schuler (Universidad Austral de Chile) for the ^{137}Cs analysis. Special thanks are due to Brian F. Atwater (USGS at Department of Geological Sciences, University of Washington, USA) who corrected the English language and gave essential scientific comments. The research was supported by FONDECYT (1980529) and DIUC (96.310.021-1.1).

REFERENCES

Aguirre L, Hervé F, Godoy E. 1972. Distribution of metamorphic facies in Chile. *Kristallinum* **9**: 7–19.

Alvisi F, Frignani M. 1996. ^{210}Pb-derived sediment accumulation rates for the central Adriatic Sea and crater lakes Albano and Nemi (central Italy). *Memorie dell'Istituto Italiano di Idrobiologia* **55**: 303–320.

Anderson TW. 1974. The chestnut pollen decline as a time horizon in lake sediments in eastern North America. *Canadian Journal of Earth Sciences* **11**: 678–685.

Appleby PG, Oldfield F. 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena* **5**: 1–8.

Appleby PG, Oldfield F. 1992. Application of ^{210}Pb to sedimentation studies. In Uranium-series Disequilibrium. Applications to Earth, Marine and Environmental Sciences, Ivanovich, Harmon RS (eds). Oxford Science Publication: Oxford; 731–778.

Auer M, Johnson A, Penn M, Effler S. 1996. Pollutant sources, depositional environment, and surficial sediments of Onongada lake, NY. *Journal of Environment Quality* **25**: 46–55.

Aztorquiza O. 1929. *Lota, antecedentes históricos con una monografía de la Compañía Minera e Industrial de Chile*. Sociedad Imprenta y Litografía Concepción: Concepción.

Battarbee RW, Appleby PG, Odell K, Flower RJ. 1985. ^{210}Pb dating of Scottish lakes sediments, afforestation and accelered soil erosion. *Earth Surface Processes and Landforms* **10**: 137–142.
Binford MW. 1983. Paleolimnology of the Peten lake district, Guatemala. *Hydrobiologia* **103**: 199–203.
Binford MW, Brenner M. 1986. Dilution of ^{210}Pb by organic sedimentation in lakes of different trophics states, and application to studies of sediment-water interactions. *Limnology and Oceanography* **31**: 584–595.
Binford MW, Brenner M. 1989. Resultados de estudios de limnología en los ecosistemas de Tiwanaku. In *Arqueología de Lukurmata*, Vol. 2, Kolata A. (ed). Instituto Nacional de Arqueología y Producciones Pumapunku, La Paz, Bolivia: 213–236.
Binford MW, Brenner M, Engstrom DR. 1991. Patrones de sedimentación temporal en la zona litoral del Huiñaimarca. In El lago Titicaca, Dejoux C, Iltis A (eds). ORSTOM-Hisbol: La Paz; 47–58.
Blais JM, Kalff J. 1995. The influence of lake morphometry on sediment focusing. *Limnology and Oceanography* **40**: 582–588.
Boer DH. 1994. Lake sediments as indicators of recent erosional events in an agricultural basin on the Canadian prairies. In *Variability in Stream Erosion and Sediment Transport* (Proceedings of the Camberra Symposium). Olive LJ, Loughran RJ, Kesby JA (eds). IAHS Publication: Oxfordshire; 125–132.
Brenner M, Binford MW. 1988. A sedimentary record of human disturbance from Lake Miragoane, Haiti. *Journal of Paleolimnology* **1**: 85–97.
Brenner M, Leyden B, Binford MW. 1990. Recent sedimentary histories of shallow lakes in the Guatemalan savannahs. *Journal of Paleolimnology* **4**: 239–252.
Cisternas M, Araneda A, Retamal O, Urrutia R. 1997. Variaciones históricas en las tasas de erosión-sedimentación de un cuerpo lacustre antropizado. *Revista de Geografía Norte Grande* **24**: 151–156.
Cisternas M, Martínez P, Oyarzún C, Debels P. 1999. Caracterización del proceso de reemplazo de vegetación nativa por plantaciones forestales en una cuenca lacustre de la Cordillera de Nahuelbuta, VIII Región, Chile. *Revista Chilena de Historia Natural* **72**: 661–676.
Contesse D. 1987. Apuntes y consideraciones para la historia del Pino radiata en Chile. *Boletín de la Academia Chilena de la Historia* **97**: 351–373.
Dearing J. 1991. Lake sediments records of erosional processes. *Hydrobiologia* **214**: 99–106.
Dearing J, Hakanson H, Liedberg-Jonsson B, Persson A, Skansjo S, Widholm D, El-Daoushy F. 1987. Lake sediments used to quatify the erosional response to land use change in southern Sweden. *Oikos* **50**: 60–78.
Deevey ES, Rice DS, Rice PM, Vaughan HH, Brenner M, Flannery MS. 1979. Mayan urbanism: impact on a tropical karts environment. *Science* **206**: 298–306.
Dixit SS, Dixit AS, Smol JP, Keller W. 1995. Reading the records stored in the lakes sediments: A method of examining the history and extent of industrial damage to lakes. In *Restoration and Recovery of an Industrial Region*, Gunn JM (ed). Springer-Verlag: New York; 33–44.
Donoso C, Lara A. 1996. Utilización de los bosques nativos en Chile: pasado, presente y futuro. In *Ecología de los bosques nativos de Chile*, Armesto J, Villagrán C, Arroyo M. (eds). Editorial Universitaria: Santiago; 234–255.
Dupré M. 1992. *Palinología*. Geoforma Ediciones: Zaragoza.
Elner S, Wood C. 1980. The history of two linked but contrasting lakes in N. Wales from a study of pollen, diatoms and chemistry in sediment cores. *Journal of Ecology* **68**: 95–121.
Evans RD. 1991. The impact of sediment focusing on total residual ^{210}Pb: implications for choice of a dating model. *Verh. Internat. Verein. Limnol.* **24**: 2335–2339.
Faegri K, Iversen J. 1975. *Textbook of Pollen Analysis*. Hafner: New York.
Foster ID, Dearing JA, Simpsom A, Carter AD, Appleby PG. 1985. Lake catchment based studies of erosion and denudation in the Merevale catchment, Warwickshire, UK. *Earth Surface Processes and Landforms* **10**: 45–68.
Gaillard MJ, Dearing JA, El-Daoushy F, Enell M, Hakansson H. 1991a. A multidisciplinary study of the lake Bjaresjosjon (S Sweden): land-use history, soil erosion, lake trophy and lake-level fluctuations during the last 3000 years. *Hydrobiologia* **214**: 107–114.
Gaillard MJ, Dearing JA, El-Daoushy F, Enell M, Hakansson H. 1991b. A late Holocene record of land-use history, soil erosion, lake trophy and lake-level fluctuations at Bjaresjosjon (South Sweden). *Journal of Paleolimnology* **6**: 51–81.
Goldberg ED. 1963. Geochronology with lead-210. In *Symposium on Radioactive Dating*. International Atomic Energy Agency: Vienna; 122–130.
Hasanen E. 1977. Dating of sediments, based on ^{210}Pb measurements. *Radiochemical and Radioanalytical Letters* **31**: 207–214.
Herrera F. 2000. *Reconocimiento de la evolución trófica de Laguna de San Pedro (VIII región, Chile) durante el último siglo mediante el análisis de registros sedimentarios*. Thesis Escuela de Graduados, Universidad de Concepción.
Hilton J. 1985. A conceptual framework for predicting the occurrence of sediment focusing and sediment redistribution in small lakes. *Limnology and Oceanography* **30**: 1131–1143.
Hilton J, Lishman JP, Allen PV. 1986. The dominant processes of sediment distribution and focusing in a small, eutrophic, monomictic lake. *Limnology and Oceanography* **31**: 125–133.
Kempt AL, Anderson TW, Thomas RL, Mudrochova A. 1974. Sedimentation rates and recent sediment history of lakes Ontario, Erie and Huron. *Journal of Sedimentary Petrology* **44**: 207–218.
Millán J, Carrasco P. 1993. La forestación en la VIII Región. In *Elementos cognoscitivos sobre el recurso suelo y consideraciones generales sobre el ordenamiento agroforestal*. Faranda F, Parra O (eds). Ediciones Universidad de Concepción; Concepción; 45–70.
Millspaugh S, Whitlock C. 1995. A 750-year fire history based on lake sediment records in central Yellowstone, National Park, USA. *Holocene* **5**: 283–292.
Morales J. 1989. *El desarrollo forestal en Concepción*. Publicationes de la Universidad Academia de Humanismo Cristiano: Santiago.
O'Hara SL, Street-Perrot F, Burt TP. 1993. Accelerated soil erosion around a Mexican highland lake caused by prehispanic agriculture. *Nature* **362**: 48–51.
Oldfield F, Appleby PG, Battarbe RW. 1978. Alternative ^{210}Pb dating; results from the New Guinea highlands and Lough Erne. *Nature* **271**: 339–342.

Oldfield F, Appleby PG, Thompson R. 1980. Palaeoecological studies of lakes in the Highlands of Papua New Guinea: I. The chronology of sedimentation. *Journal of Ecology* **68**: 457–477.

Olavi S, Lichu A, Simola H. 1990. Drainage ditch erosion history as recorded in the varved sediment of a small lake in East Finland. *Journal of Paleolimnology* **3**: 161–169.

Oyarzún CE. 1997. Estudio a mesoescala de la erosión del suelo en una cuenca hidrográfica de montaña, Chile central. *Revista de Geografía Meridiano* **5**: 23–28.

Parra O. 1989. La eutroficación de la Laguna Grande de San Pedro, Concepción, Chile: Un caso de estudio. *Ambiente y Desarrollo* **5**: 117–136.

Parra O, Dellarossa V, Ugarte E. 1976. Estudio limnológico de la lagunas Chica de San Pedro, La Posada y Lo Méndez. *Boletín Sociedad de Biología de Concepción,* **50**: 73–86.

Piñones O, Tomicic I. 1995. Estudio de los niveles raidiológico-ambientales en Chile durante el periodo 1966–1994. *Nucleotécnica* **29**: 67–82.

Pourchet M, Mourguiart P, Pinglot JF, Preiss N, Argollo J, Wirrmann D. 1994. Sédimentation récente dans le lac Titicaca (Bolivie). *Comptes Rendus Academie des Sciences, Paris* **319**: 535–541.

Pourchet M, Mourguiart P, Pinglot JF, Preiss N, Argollo J, Wirrmann D. 1995. Evaluation des vitesses de sédimentation récente dans les hautes vallés des Andes boliviennes. Son intérét dans l'estimation des paléo-pollutions atmosphériques. *Comptes Rendus Academie des Sciences, Paris* **320**: 477–482.

Preiss N, Méliers M, Pourchet M. 1996. A compilation of data on lead-210 concentration in surface air and fluxes at the air-surface and water-sediment interfaces. *Journal of Geophysical Research* **101**: 28847–28862.

Robbins JA, Murdoch A, Oliver BG. 1990. Transport and storage of ^{137}Cs and ^{210}Pb in sediments of Lake St. Clair. *Canadian Journal of Fisheries and Aquatic Sciences* **47**: 572–587.

Rowan DJ, Cornett RJ, King K, Risto B. 1995. Sediment focusing and ^{210}Pb dating: a new approach. *Journal of Palaeolimnology* **13**: 107–118.

Smol, JP. 1992. Paleolimnology: an important tool for effective ecosystem management. *Journal of Aquatic Ecosystem Health* **1**: 49–58.

Spliethoff H, Hemond H. 1996. History of toxic metal discharge to surface waters of the Aberjona watershed. *Environmental Science and Technology* **30**: 121–128.

Unda A, Ravera F. 1994. *Análisis histórico de sitios de establecimiento de las plantaciones forestales en Chile*. Ediciones Instituto Forestal, Unidad de medio ambiente: Santiago.

Van der Post KD, Olfield F, Haworth EY, Crooks PR, Appleby PG. 1997. A record of accelerated erosion in the recent sediments of Blelham Tam in the English lake district. *Journal of Paleolimnology* **18**: 103–120.

Wan GJ, Stantshi PH, Sturm M, Farrenkothen K, Lueck A, Werth E, Shuler C. 1987. Natural (^{210}Pb, ^{7}Be) and fallout (^{137}Cs, ^{239,240}Pu, ^{90}Sr) radionuclides as geochemical tracers of sedimentation in Greifensee, Switzerland. *Chemical Geology* **63**: 181–196.

