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Potential of Long-lead Streamflow and Drought Forecasting in California

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Carbon Dynamics in Natural vs. Constructed Wetland Systems: Implications for Wastewater Treatment

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ABSTRACT

We investigated the roles of three tall emergent macrophytes (*Scirpus acutus*, *S. californicus* and *Typha domingensis*) in carbon cycling at a local wetland constructed for wastewater treatment and at an adjacent stream fed freshwater marsh. Combined above ground standing biomass ranged from 1125 g/m^2 in freshwater to 3192 g/m^2 in wastewater. *Scirpus acutus* (SA) densities ranged from 86 plants/m^2 in freshwater to 206 plants/m^2 in wastewater. A combination of *T. domingensis* and *T. latifolia* (TS) densities ranged from zero plants/m^2 in wastewater and freshwater to 19 plants/m^2 in wastewater. Growth rates of SA were highest for plants between 50 to 100 cm and the average maximum rate was 6 cm/day. For TS the highest rates were recorded for plants between 0 and 50 cm and the average maximum rate was 4.5 cm/day. Growth for both SA and TS slows at heights between 2.5 and 3 m. Both SA and TS are subjected to grazing, TS more so than SA and there is no difference if they are in freshwater or wastewater. Carbon to nitrogen ratios vary throughout the year with the fall ratios indicating much higher carbon in the above ground biomass. Decomposition rates of above ground material in the water column vary within the wastewater treatment system with material closer to the inflow of wastewater having slower rates than those furthest from the inflow. Decomposition of below ground biomass, buried at -15 cm, is much faster for TS than for SA.

A mesocosm study investigating biomass and nutrient allocations indicates that the ratio of above ground biomass to below ground biomass changes with nutrient availability. In low nutrient situations the ratio for SA and *T. domingensis* (TD) ranged from 0.3 to 0.4 (over 70% of the biomass below ground). In high nutrient situations SA had a ratio of 1.2 and TD had a ratio of 0.7.

A water level competition experiment indicates that SA establishes quicker than TD or *S. californicus* (SC). However, after one year SA gives way to SC in deeper water (50-80 cm) and maintains dominance in shallower water (10-40 cm). TD was the slowest starter and had the lowest percent cover of all three species after one year (24%).

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PROBLEM AND RESEARCH OBJECTIVES

University of California Water Resources Center (WRC) project W-855 focused on obtaining data on carbon budgets at a constructed wetland in California's Central Valley. Wetlands are important components of the landscape. Wetland values such as water quality improvement and providing wildlife habitat are determined by basic ecosystem functions e.g., primary productivity and nutrient cycling. These functions involve biogeochemical processes carried out by wetland plants and soil microorganisms (Mitsch and Gosselink 1993). It has been recognized that these processes are valuable for the treatment of human generated wastewaters (Wetzel 1993). Constructed wetlands are being designed as alternatives to high energy wastewater treatment systems, especially in rural areas where the necessary land acreage is available (Water Pollution Control Federation 1990).

The role of wetland plants in treatment systems is slowly being defined. Some authors support the ideas that emergent plants (macrophytes) act as substrate for the attachment of microorganisms which actually perform the critical clean-up processes. It has also been claimed that plants provide substrate aeration by root release of oxygen. Another popular view is that plants provide continual water treatment by nutrient and pollutant uptake (Reed et al. 1988, Hammer and Bastian 1991, Tchobanoglous and Burton 1991). However, it has been shown that each of these processes have limited applications. A more realistic approach to water treatment involves the selection of plants to meet well defined treatment objectives (Kadlec and Knight 1996).

With few exceptions, emergent macrophytes provide the largest pool of photosynthetically produced organic carbon in wetlands constructed for wastewater treatment. Some questions concerning the role of these plants in the treatment processes can be answered by quantifying the pools and fluxes of carbon they generate. Our overall objective was to elucidate the role of three large stature, Central Valley dominant macrophytes in carbon transformations. By focusing on these extremely important

processes we hope to contribute to the basic understanding of energy flow through wetland ecosystems. This information will also fill in important gaps in the modeling and design of constructed wetlands for wastewater treatment.

The specific objectives of our WRC grant were:

1. Measure the net primary production (NPP) of three wetland plant species and determine their biomass allocation into the above and belowground components

2. Asses the death rates of both the aboveground and belowground plant parts

3. Quantify the decomposition rates of both the aboveground and belowground plant parts

4. Estimate the translocation of biomass (shoots to rhizomes in the fall and rhizomes to shoots in the spring)

5. Asses the tolerances of individual species to varying water levels

6. Record the effects of herbivory

The majority of the research for WRC project W-855 was conducted at the Sacramento County Demonstration Wetlands in Elk Grove, California. This is a five year, large scale pilot project investigating the use of constructed wetlands in the treatment of municipal wastewaters. At the completion of W-855 there are still two years of work to do before the completion of the County project. Therefore much of the research is continuing at the time of this report.

METHODS

Description of the Study Sites

Sacramento Demonstration Wetlands

The Sacramento Regional County Sanitation District (SRCSD) has developed an 8.9 ha free water surface constructed wetlands project on the northeast area of the

bufferlands that surround the Sacramento Regional Wastewater Treatment Plant (SRWTP) in Elk Grove, California (Figure 1). The climate is characteristic of the Central Valley, with hot dry summers and cool wet winters.

The three main objectives of the demonstration wetland project are:

1. Characterize constructed wetland treatment performance
2. Identify the fate of specific constituents of concern, such as metals, in wetlands
3. Develop and evaluate constructed wetlands management procedures

The research conducted for WRC project W-855 was in partial support of these objectives.

The demonstration wetlands consist of ten treatment cells and one control cell that are approximately 384 m in length and 15 m in width (Figure 2). Also located on the site is a .8 ha habitat wetland (as opposed to a treatment wetland) with two vegetated islands. The habitat wetland provides a location to conduct research without the constraints of the designed treatment cells.

The treatment cell inlets are located on the north end of the B-half of the cell. Wastewater enters the cell here, travels south on the B side, crosses into the A side via a 20 cm pipe and then travels north to the effluent structure on the north end of the A-half cell. Wetland treated wastewater then goes to the habitat wetland prior to its return to the SRWTP. Each half cell has a non-vegetated, 1.5 m deep mosquito fish pool located at the midpoint and at each end. These pools provide refuge for the fish in the event water levels must be drawn down for cell maintenance. Detailed design criteria and characteristics are in Table 1.

The vegetation of the treatment cells is dominated by *Scirpus acutus* (SA), *Typha domingensis* (TD), and *Typha latifolia* (TL). Cell 8 was initially planted with seeds of *Scirpus americanus*. A combination of the two *Typha* species (TS will be used when the species is unknown) quickly established themselves in that cell and dominated it in 1995. After intensive management and replanting in 1996, cell 8 is currently dominated by *Scirpus californicus*. (SC). It should be noted that recent taxonomic changes have resulted in the reclassification of *Scirpus* to the genus *Schoenoplectus* (Smith 1995). However, this report will continue to refer to *Scirpus*, according to standard California reference, the Jepson Manual (Hickman, 1993).

Five treatment processes are being investigated for the wetlands demonstration project; plug flow (cells 7-10), recycle (cells 3 and 4), batch discharge (cells 1 and 2), a combination of overland flow and plug flow (cell 6) and a combination of subsurface flow and plug flow in cell 11. Cell 5 is a project control and receives only ground water. Within the plug flow treatment (cells 7-10) we are investigating the effects of different plant

species, water depth and open water on the treatment processes. Table 2 summarizes these treatments (Nolte and Associates.1997, 1996)

Laguna Creek

Laguna creek is a relatively small suburban creek in central Sacramento County. Its watershed borders that of Elder Creek and Deer Creek and is approximately 14,000 ha. Under existing conditions its 100 year and 2 year mean annual flows are 16.7 m^3/s and 83.8 m^3/s respectively (Water Resources Division 1996). The study areas used are on Sacramento County bufferland property. Five 1 m^2 permanent quadrats were established in well developed stands of *Scirpus acutus*.

UC Davis wetland plant cultivation facility

The UC Davis wetland plant cultivation facility is located on the UC Putah Creek Preserve next to the Institute of Ecology lab and the Aquaculture and Fisheries facility. A mesocosm study investigating biomass allocation was performed here.

Determination of Carbon Pools and Fluxes

Plants

101 permanent quadrats were established using 1.2 cm diameter PVC pipe at the four corners of a square meter at the SRWTP wetland and an additional five were established at Laguna Creek in March of 1994. The locations of the sampling quadrats within the cell are presented in figure 3. Initial rational for placement of the nine quadrats per cell was to determine if changes occurred along the direction of water flow. Because of the different layout for cells 6 and 11 an additional quadrat was placed in each. Due to vigorous plant growth, unexpected plant size, and eventual removal of pipe markers by machinery operators, most of the permanent quadrats were destroyed. A random quadrat was placed in the general vicinity instead. For the brevity of this report, only data gathered from cells 1, 5 and 7 will be presented.

At each quadrat we recorded plant species composition, density, height, incidence of herbivory, and water depth. This was conducted during peak biomass (late summer).

Biomass

We harvested two TS plants and two SA shoots near each of the 101 quadrats in 1994. In 1996 two additional plants of each genus were again harvested from every quadrat location. The lengths of the harvested plants were measured and the plants subsequently oven dried and weighed. A simple regression of dry weight (y) on the plant height (x) was calculated for SA. A height index was calculated for TS using the average length of the four tallest leaves multiplied by the total number of leaves in the entire plant. The dry weight of the entire plant was regressed on the height index.

Leaf Area

In 1995 thirty six leaves of TS and thirty one shoots of SA were measured for leaf area using a LI-COR 3000A leaf area meter. The leaf area (y) was then regressed on leaf length (x). For TS the area is for only one side of the leaf. Measurement of the area of SA shoots is more problematic since the shoots are round. Each shoot was flattened prior to measurement so the result represents half of the total shoot surface area.

Growth

Individual shoots of SA and SC and whole plants of TS were marked and information on plant height, plant condition, and herbivory were recorded. Plant condition included dead plant tips, broken tips, plant tips in the water, senescence evidenced by green only near the water and the remaining shoot being dead, and completely dead plants. The height of the first bend was also recorded. This information is used for assessing rates of growth, grazing and senescence. Plants were recorded within a specified area so density and production can also be determined.

In the winter of 1995-96 five to ten individuals of SA in cells 1, 3, 5, 7, and 9 and twenty individuals of SC in the habitat cell were tagged and monitored on a weekly basis. From September of 1996 until January 1997 new SA and TS were tagged and monitored. In February 1997 SA and SC were tagged and monitored until the time of this report.

Biomass allocation

A mesocosm experiment was conducted in 1995 to examine the effects of nutrients (nitrates) on the growth of SA and TD and to determine the allocation of nutrients

(nitrogen) to plant shoots, roots and rhizomes. This experiment was conducted at the wetland plant facility located on the UCD Putah Creek Preserve.

Four rhizome cuttings were planted 15 cm deep in each of twenty four 90 L tubs. The soil used was a sandy loam. Water levels were kept constant at 15 cm above the soil surface. Three planting treatments were used: SA alone, TD alone, and a combination of both species. Four replicates of each of the planting treatments were subjected to either a high nutrient treatment (210 parts per million (ppm) NO_3-N) or a low nutrient treatment (less than 1 ppm). Rhizome fresh weight was recorded prior to planting and five cuttings of each species were weighed fresh, oven dried and reweighed. This resulted in a regression of wet weight (x) to dry weight (y).

Tubs were watered every two days. Nitrate levels were kept constant by analyzing the water using an Orion ISE hand held electrode. A nutrient solution containing calcium nitrate ($Ca(NO_3)_2$) and potassium nitrate (KNO_3) was added to adjust the nitrate concentration back to the desired level.

At the end of sixteen weeks the plants were harvested and the shoots, roots and rhizomes were separated. Shoot lengths were measured. All plant material was oven dried at 80° C and weighed. Ratios of above ground to below ground biomass were calculated. Plant parts were ground and analyzed for carbon, hydrogen and nitrogen using a Perkin Elmer 2400 CHN Elemental Analyzer.

Nutrient allocation

The allocation of nutrients between shoots and roots was determined by harvesting both above and below ground plant material for SA and TS from Laguna Creek and the SRWTP wetland. Samples were collected at various times throughout the year. Plant samples were analyzed for percent organic matter (OM) using loss on ignition, total kjeldahl nitrogen (TKN) and total phosphorous (TP) using the ammonium molybdate colorometric method measured on a spectrophotometer set at 650 nm (Horwitz 1980).

Decomposition

Decomposition rates were determined using the litter bag method (Newell and Fallon 1989). Senescent aboveground shoot material of SA and TS was collected in February 1995. The material was cut into 10-15 cm segments and the entire batch was well mixed. Ten grams of this fresh (not dried) material was placed into nylon mesh bags (2

mm mesh size) and placed within the the water column. Seven 10g replicates of TS and nine 10g replicates of SA were oven dried and weighed to determine the average initial dry weight of all samples. Three groups of five bags of each species (30 total bags) were secured to a wooden stake and suspended in the water column of the first and ninth quadrats of cells 1, 5, 7 and 9. Additional groups were placed in the water at two locations along Laguna Creek.

One mesh bag from each group was recovered in July 1995, January 1996, June 1996, February 1997 and June 1997. The recovered bags were rinsed gently under fresh water, opened to reveal the contents, picked over to remove foreign debris and invertebrates (visible to the naked eye), oven dried and weighed. If the bag material was contaminated with sediment (as most of the Laguna Creek samples were) the sample was allowed to soak in 5g Calgon per liter of water, which allows soil particles to disperse. Soaking was followed by a gentle freshwater rinse.

Below ground material was collected in April 1996. In addition to rhizomes of both SA and TS we collected basal sections of TS since the morphology of TS gives it this large piece of biomass that is below ground. Due to the varying lengths and sizes of these materials, they were cut into various lengths, measured, and the fresh weight recorded. Four to eleven additional samples of SA and TS rhizomes and TS bases were weighed, oven dried and reweighed to determine the initial dry weight of all samples.

The fresh sample pieces were placed inside nylon mesh bags (2 mm mesh size) and buried 15 cm beneath the soil surface in cells 1A, 5A, 5B, 7A, 7B and Laguna Creek. Two bags of each sample type were recovered in October 1996 and April 1997. The contents of each bag were gently rinsed with fresh water to remove sediment, oven dried and weighed to determine percent loss. As of the April 1997 processing, we have not had to use Calgon to disperse soil particles.

Data were calculated as percent of original material remaining and transformed using an angular transformation. Time, in months, was transformed using a $\log(1 + x)$ function. Regression curves of biomass onto time were calculated. The resulting curves were then compared using a modified t-test according to Zar (1984).

Plant Tolerance to Varying Water Levels

An experiment was set up at the SRWTP wetland habitat cell to determine plant responses to varying water levels in conjunction with competition between SA, SC and TD.

In June of 1994 rhizomes of the three species were planted approximately 50 cm apart in fifteen lines of varying elevation according to the pattern presented in Figure 4. They were irrigated until established and any rhizomes that failed to sprout were replaced until 100 % establishment success was achieved. At this time the water level of the cell was slowly raised to design level. This left those plants closest to shore in 10 cm of water and those furthest from shore in 80 cm of water. Since establishment, water levels have been manipulated such that summer levels are 20 cm lower than winter levels.

Plants were first monitored in September of 1994 by counting the number of SA and SC shoots and measuring the length of the tallest, shortest, and average shoot height per plant. Individual TD leaves were counted and the total number of shoots per plant were counted. The tallest, shortest, and average height of the leaves were measured. A regression was used to determine biomass. This method was possible due to the small size of the plants.

A different monitoring method was required in November 1995 due to tremendous plant growth in both the horizontal and vertical directions. A 3 m pole, marked off at 10 cm intervals was pushed horizontally through the plant canopy close to the water surface. Both ends of the pole were located in the same depth of water. Measurements were started at the open water-vegetation boundary of the experiment in 80 cm of water. Plant species and height were recorded at each end of the pole and every 10 cm along the length of the pole, using a point-intercept method. Plant species closest to the mark (within 1 cm) were scored. If no plants were encountered a score for open water was recorded.

The pole was then moved towards shore to a new location in a water depth 10 cm shallower and the above procedure was repeated. When TD was encountered, the number of leaves of the plant, as well as the length of the encountered leaf were recorded. It was also noted when two or more leaves of the same plant were encountered at different marks. The number of plants identified for each species and the number of encounters of open water were each divided by the total number of possible encounters. This is considered the percent cover for the species (Mueller-Dombois and Ellenberg 1974).

Photosynthetic Rates

Carbon Dioxide (CO_2) fixation rates were determined for SA and TS using a LI-COR 6200 Photosynthesis Meter. A diurnal curve was developed for each species by taking readings from five to seven shoots every two hours throughout the day. Measurements were taken in August 1995.

Sediment

SRWTP wetland sediment samples were taken in 1996 along the gradient of influent to outflow of the treatment cells. Samples were collected using a hollow PVC pipe driven to a minimum depth of 15 cm. The entire core was then homogenized and analyzed for total organic carbon, total kjeldahl nitrogen, and total phosphorous. Results from this sampling event are reported for cells 5 and 7 only.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Plants

Table 3 summarizes the data from the 1995 and 1996 quadrat monitoring events. Cell 5 generally has the highest % cover for *Lemna* spp., a small floating plant. This indicates a more open canopy since a closed canopy eliminates light at the water level. Densities of SA are highest in cell 1 and lowest in cell 5. Densities of TS are more evenly distributed amongst the cells.

Biomass

The regression of dry weight biomass on shoot length (SA) and height index (TS) for 1994 plants is presented in Figures 5 and 6 respectively. The 1996 data are presented in Figures 7 and 8, respectively. Note that the TS dry weight is for an entire plant whereas the SA dry weight is for one shoot.

There is a distinct difference in SA biomass between the locations within each year and also between the years sampled (table 3). Cell 5 and Laguna Creek (freshwater) have lower SA biomass than cells 1 and 7 (1125 and 1123 g/m^2 compared to 1673 and 1545 g/m^2 respectively for 1995 and 1866 and 1710 g/m^2 compared to 2454 and 2228 g/m^2 respectively for 1996). Data indicate that there was a substantial biomass increase from 1995 to 1996. Cell 5 has the lowest SA biomass of all the treatment cells (data not shown).

TS does contribute to overall biomass in the quadrats located at the demonstration wetland. In 1995 TS made up 25% of the total biomass for all demonstration wetland cells. In 1996 TS made up 30% of the biomass in cells receiving wastewater and only 12% in cell 5, the groundwater control.

Leaf Area

The regression of leaf area on shoot length (SA) and leaf length (TS) is presented in figures 9 and 10 respectively. Any length of SA shoot produces a smaller leaf area than the same size TS leaf. This makes sense when the shape of the leaves are considered. Leaves of TS tend to remain wider towards the tip than SA shoots, which taper the entire length.

Because the leaf area is based on leaf length (as is biomass), it should be expected that cell 1 would have the higher leaf area and cell 5 the smaller. This is indicated in table 3.

Growth

A comparison of growth rates for SA and TS in wastewater and controls is presented in figures 11 and 12 respectively. For SA, the average maximum growth rates are achieved when the plants are between 50 to 100 cm. In this size range the plants grow at an average of 6 cm per day. The maximum growth rate recorded was 28.8 cm per day. The rate of increase slows until the plant reaches a height between 2.5 and 3 meters. Growth past this point is slow and once it stops the plant tips begin to break off, resulting in negative growth rates (fig. 11). The highest average growth rate for TS is almost 4.5 cm per day and this occurs between the sizes of 0 to 50 cm. The maximum growth recorded for TS was 18.1 cm per day. Growth of TS also slows at 2.5 to 3 m (fig. 12).

Table 4 presents the percentage of plants that were produced after the start of the monitoring and the percentage of plants that died during the monitoring. Note the lack of new growth in locations receiving fresh water (cell 5 and Laguna Creek).

Table 4 also presents the percent herbivory of all plants monitored in the fall of 1996. For the selected locations, the percent of plants grazed ranges from 0 to 78% for SA and 0 to 86% for TS. There is no indication that wastewater or well water influence the incidence of herbivory. The 1996 quadrat data indicate a higher incidence of herbivory on TS (23%) than on SA (0.4%) (data not shown).

The average length of time that a plant remains in a certain growth stage (growing, mature, senescent, dead but standing up) is presented in Table 5. Due to high herbivory, where a plant can go from a growing plant to a dead plant within 1 minute, the values for dead standing plants and senescent plants may be skewed. If a plant is not eaten, it will remain in those two stages for a longer period of time.

Biomass Allocation

In the SA monocultures, the high nutrient treatment reached cumulative shoot lengths per tub of 150-200m while the low reached 20-25m (Fig. 13). Results were similar for the TD monocultures (Fig 14). The mixed tubs resulted in lower lengths, but they started with half the number of rhizomes (2 vs. 4). The results for the mixed SA and TD are presented in figures 15 and 16 respectively.

Above to below ground biomass ratios are presented in figure 17. For low nutrient treatments the ratio was 0.3 to 0.4. This means that 71-77% of all biomass is allocated to belowground plant parts (rhizomes and roots). For high nutrient treatments the opposite was true. Here the ratio was 1.2 for pure SA treatments, 0.8 for SA in mixed treatments, 0.7 for TD in pure treatments, and 1.0 for TD in mixed treatments. These ratios show that in the high nutrient treatments, SA allocated 45-56% of its biomass to belowground and 44-55% above ground, i.e. about half and half. TD showed 50-59% belowground and 41-50% above ground. TD allocated slightly more of its biomass belowground than above even in the high nutrient treatments.

Total biomass numbers for the mesocosm experiments range from 1140 g/m2 for the low nutrient treatment to 5100 g/m2 for the high nutrient treatment. Keep in mind this is total biomass, above and below ground. The difference between SA and TD was not significant. Relative growth rates (RGR) were calculated for SA and TD and are presented in Fig. 18. The high nutrient treatments had higher RGR's than the low nutrient treatment. The mixed species treatment had the same RGR within a species as the single species treatment.

Nutrient Allocation

Average concentrations of carbon, nitrogen, and phosphorous found in plant shoots and rhizomes at the demonstration wetland are presented in Table 7. Although samples were analyzed for percent organic matter (%OM), the data are presented as percent total organic carbon (%TOC), using the following regression:

$$\%TOC = (0.535 \times \%OM) - 0.2$$

(Rejmankova unpublished results). Carbon concentrations range from 16 to 29.5 %, nitrogen ranges from 0.5 to 3.1 %, and phosphorous ranges from 0.07 to 0.45 % for all samples throughout the year. The C:N:P ratios show a trend of higher ratios for above ground material and higher ratios for plants growing in fresh water (cell 5 and Laguna Creek).

Table 6 presents the nitrogen content of the roots, shoots, and rhizomes (calculated as percent of the plant part that is nitrogen) of the plants in the mesocosm experiment. The average nitrogen content of SA and TD rhizomes was 1.41% and 1.18% respectively in high nutrient/single species treatments. The average nitrogen content of SA and TD shoots was 0.9% and 1.55% respectively in high nutrient/single species treatments.

Decomposition

Above ground Litter

Figures 19 - 26 present decomposition curves for SA and TS litter in the water column of cells 1, 5, 7, and Laguna Creek. For both species, the two wastewater cells, 1 and 7, show the effluent side of the cell (quadrat 1/9 and 7/9) to have faster rates of decomposition than the influent side (quadrat 1/1 and 7/1). This is in contrast to the well water control, cell 5, which has a faster rate of decomposition for both litter types in the influent side. Of the two wastewater treatment cells, cell 1 has faster decomposition rates for both litter types in the water column than cell 7.

Results of the t-test comparison of regression lines for litter decomposition are presented in Table 8. There are significant differences ($p<0.01$) between the rates of decomposition for SA litter in the two half cells of one and seven (S1A, S1B and S7A, S7B) and between the rates found in cell 5 and cell 7 (S5, S7). Decomposition of TS had no significant differences between cells, however there was a slight difference between cells 5 and 7. There was a significant difference between the decomposition of SA and TS in the Laguna Creek locations.

Determination of half life of above ground material results in cell 5 having the shortest (< 1 yr.), cell 1 and Laguna Creek having a $t_{1/2}$ close to one year and cell 7 having the longest (> 1.5 yr). It is not surprising that cell 1 and Laguna Creek are similar since the hydrology of both locations allowed for periodic drying.

Below ground biomass

Figures 27 - 32 present the decomposition curves for buried SA and TS rhizomes at the demonstration wetlands and Laguna Creek. Overall, TS rhizomes appear to decompose quicker than SA rhizomes. There appears to be no difference in belowground decomposition between cell 7 (wastewater) and cell 5 (well water).

Figure 33 presents the decomposition curves for TS bases buried in a wastewater treatment cell (7) and the well water control cell (5). The water source appears to have no influence on the decomposition of these plant structures. In comparing the curves of TS rhizomes and TS bases, it appears as though the bases have a slightly slower decomposition rate.

Results of the t-test comparison of regression lines for rhizome decomposition are presented in Table 9. There are no significant ($p<0.01$) differences between any of the lines compared. Decomposition of TS rhizomes are significantly ($p<0.05$) quicker than for SA rhizomes in cell 5 (Figs. 28 & 29).

Rhizome half life varies from 6 months (TS) to > 1 yr (SA). Rhizomes of SA appear to have more woody tissue, whereas TS rhizomes are generally more flexible. The basal pieces of TS have a half life close to 9 months.

When comparing decomposition rates between litter in the water column and buried rhizomes there is a highly significant ($p<0.001$) difference for TS in cell 7 (wastewater) and a significant difference ($p<0.01$) for TS in cell 5 (well water) (Table 10). There appears to be no difference for SA in either location.

Plant Tolerance to Varying Water Levels

Figure 34 shows the results of the initial monitoring completed in September of 1994 (3 months after planting). At that time SA had a greater number and taller shoots than SC resulting in more biomass per planted row. Biomass of TD appears to be very low. Peak biomass for SA is at a water depth of just below 50 cm. Peak biomass for SC is at a water depth of just below 40 cm and TD found its maximum around 30 cm.

Table 11 shows the percent cover for each species and open water for the various water depths in November 1995. A two factor ANOVA showed no significant difference between species cover at varying water levels. However, SA appears to have higher average coverage in the shallow water (38.7 %) than SC (29.85%). This trend is reversed for the deeper water where average SC cover is greater (43.5%) than SA (23.4%). Values for TD remained constant as did the values for open water.

A two factor ANOVA with vegetation height as the dependent variable resulted in a significant difference between species ($p=.0277$) and water levels ($p=.0095$). Three post-hoc tests (Fisher's Protected LSD, Tukey-Kramer and Games-Howell) all show the height of SA being significantly lower than the height of either SC or TD with no difference between the later two species. Plant heights in the 10 cm water depth transect were significantly shorter than in all other depths. There was no interaction between plant height

and water levels. The average height for SA, SC and TD was 266, 317 and 309 cm respectively. There was also no clear trend for the number of leaves per TD plant at various water levels. The average number of leaves per plant was 8. One TD plant (10 leaves) was intercepted three times in 80 cm of water and one plant (10 leaves) was intercepted twice in 20 cm of water. All other TD scores were from separate plants.

Ludwigia peploides and *Polygonum hydropiperoides* were present in the 20 and 10 cm water depth transects.

Photosynthetic Rates

Figures 35 and 36 present the diurnal curves of photosynthetic rates for SA and TS respectively. There is not a great difference in the curves. Both species reach a rate of 12 μmol m^{-2} s^{-1} by 0800. The highest rates (around 17 μmol m^{-2} s^{-1}) occur between noon and 1400. These measurements were taken from plants in a wastewater treatment cell on a clear hot day. We would expect that these rates are close to the maximum potential that these species are capable of. Knapp and Yavitt (1995) found similar results from *Typha latifolia* at similar latitudes (maximum net photosynthesis of 20 μmol m^{-2} s^{-1}).

Sediment

Table 12 presents the results of the sediment sampling event in 1996. Cell 7 (wastewater) has significantly (t-test, $p<0.001$) higher levels of nitrogen than cell 5 (well water). All constituents show a pattern of lower concentrations near the beginning and end of the run, however this is not significant. The resulting C:N:P ratios are 59:4:1 for cell 5 and 62:7:1 for cell 7. This also reflects the higher nitrogen levels in cell 7.

CONCLUSIONS

Due to their large stature, tall emergent macrophytes are often viewed as similar in their functioning in wetland ecosystems. We have found this to not be true. There are differences between how each of the plant types investigated behave in their carbon cycling.

Apparently SA and TS fix atmospheric carbon (photosynthesize) at fairly similar rates, but they allocate that fixed carbon differently. In low nutrient conditions both allocate more carbon to their below ground structures (roots and rhizomes). As nutrient levels increase more carbon is allocated above ground, but SA seems to do this to a greater

extent. With increasing nitrogen, SA will apportion more N to below ground biomass whereas TD in the same situation will allocate the N to above ground biomass. Although there was no difference between grazing in high nutrient areas and low nutrient areas, TS was grazed more than SA. This may be due to the availability of N in the above ground biomass.

The allocation of nutrients is also dependent on the time of year. In the late fall there is a greater apportionment of N to below ground than to above ground for both SA and TS.

Decomposition of the above ground material showed no major differences between the species (only between the locations). However, there was a difference in below ground decomposition. TS rhizomes decompose faster than SA rhizomes. This seems counter intuitive since SA is putting more N below ground. SA rhizomes are firmer and woodier than TS rhizomes which may slow decomposition. Also these results may be an artifact of the two experiments conducted. The mesocosm experiment (resulted in high SA rhizome N) analyzed rhizomes from fairly young plants (less than 1 year) and the rhizomes used for the litter bag study (resulted in slower SA rhizome decomposition) are of an undetermined age (most likely over one year).

Establishment and growth of the plants investigated also varied. The quickest to establish was SA, however after one year it no longer dominated the entire plot. Instead, SA dominated the shallow water areas (10 to 40 cm). A longer establishment time was observed in SC but after one year it dominated the deeper water areas (50 to 80 cm). The slowest starter was TD and even after one year it only occupied 24% of the area.

Given this information the following conclusions can be made for the three species studied:

1. In treatment systems, tall emergent plants will have about as much biomass below ground as above ground.
2. Above and below ground biomass have very different C:N ratios throughout the year. In the fall the above ground biomass is much higher in carbon.
3. Decomposition in the water column varies within treatment systems with slower rates near the influent.
4. Decomposition occurs much faster if the material is exposed to periodic drying.
5. Grazing occurs on TS more frequently than SA in any type of water (fresh or wastewater).
6. When new treatment systems are established, the plant species composition may change depending on initial species selection and operational water depth. Select SA for shallower areas and SC for deeper areas.

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Table 1. Demonstration wetlands design criteria and characteristics

Criteria	Value
Length	384 m
Width	15.25 m
Aspect Ratio (L:W)	25:1
Dominant Vegetation	*Scirpus acutus, S. californicus*
	Typha domingensis, T. latifolia
Operating Depth	15 to 60 cm
Maximun Project Flow Rate	4542.5 m^3/d
Average Influent Flow Rate	265 L/min
Hydraulic Loading	654.75 m^3/ha
Detention Time	3 to 13 days
Habitat Cell Depth	0 to 2.1 m
Mosquito Fish Pothole	3 per cell, 12.1 m x 15.25 m x 1.5 m deep for fish refuge

Table 2. Operational status of wetland treatment cells

Cell	Treatment Process	Operational Status
1 & 2	Batch Feed	Fill (8-14 days) and drain (1 day)
3 & 4	Recycle	1:1 recycle rate
5	Control	Plug Flow with Groundwater
6A & 6B	Overland Flow	6A-day, 6B-night
7 to 10	Plug Flow	7-control, 8-*Scirpus californicus*, 9-open water, 10-lower level
11	Subsurface-Plug Flow	Gravel bed near influent

Table 3. Summary of quadrat data from 1995 and 1996

	Date	Lemna (%) cover	SA Biomass g/m2	SA Leaf area m2/leaf/m2	SA Density plants/m2	SA Dead plants/m2	TS Biomass g/m2	TS Leaf area m2/leaf/m2	TS Density plants/m2	TS Dead plants/m2
Cell 1 Average	8/22/95	11	1673	7.28	206	61	564	2.89	10	37
Cell 1A	8/22/95	26	1549	7.02	218	54	0	0	0	0
Cell 1B	8/22/95	0	1772	7.49	197	66	1015	5.21	18	67
Cell 5 Average	8/21/95	60	1125	4.77	131	100	335	2.29	13	36
Cell 5A	8/21/95	76	1118	4.73	121	81	503	3.56	21	67
Cell 5B	8/21/95	48	1129	4.8	138	114	201	1.28	6	11
Cell 7 Average	8/29/95	1	1545	6.4	158	99	587	3.14	9	94
Cell 7A	8/29/95	3	1663	6.87	175	123	236	1.21	3	131
Cell 7B	8/29/95	0	1451	6.03	145	79	867	4.68	14	64
Laguna Creek Av	9/7/95	0	1123	5.9	171	114	2	0.03	1	22
Cell 1 Average	8/26/96	0	2454	6.49	201	115	1152	5.84	19	32
Cell 1A	8/26/96	0	2768	7.56	243	150	51	0.5	3	0
Cell 1B	8/26/96	0	2204	5.63	169	87	2033	10.1	31	58
Cell 5 Average	9/3/96	59	1866	3.49	86	134	267	1.53	7	71
Cell 5A	9/3/96	58	1724	3.25	80	109	210	1.58	9	85
Cell 5B	9/3/96	60	1980	3.68	90	154	312	1.49	6	60
Cell 7 Average	9/9/96	7	2228	4.81	126	96	964	4.21	16	54
Cell 7A	9/9/96	0	2241	5.05	138	122	465	1.99	5	30
Cell 7B	9/9/96	14	2217	4.62	117	74	1363	5.99	24	73
Laguna Creek Av	9/9/96	0	1710	4.09	134	142	0	0	0	0

Table 4. Percent of new shoots/leaves produced, the percent of shoots/leaves that died and the percent showing evidence of herbivory over an eleven week period in the late fall of 1996.

	LOCATION	NEW	DEAD	HERBIVORY
Scirpus	1/1	4	7	11
	1/9	2	1	14
	5/1	0	7	78
	5/9	1	7	6
	7/1	1	6	8
	7/9	3	7	23
	LC3	1	1	0
	LC4	0	3	0
Typha	1/1	1	6	17
	1/9	4	4	22
	5/1	0	1	38
	5/9	0	4	0
	7/1	10	3	24
	7/9	2	2	86
	LC3	0	1	9
	LC4	0	2	0

Table 5. Number of days a shoot or leaf remained in a life stage catagory, fall/winter 1996. G-growing, M-mature, S-senescent, D-dead, ND-no data

	CELL #	G	M	S	D
Scirpus	1	35	45	17	17
	5	80	38	48	48
	7	54	42	18	18
Typha	1	62	48	12	6
	5	ND	40	12	17
	7	45	41	11	ND

Table 6. Nitrogen content (%) in various plant parts of the mesocosm experiments. S=*Scirpus*; T=*Typha*; M=Mixed culture; C=Monocluture; H=High nutrient; L=Low nutrient, ND=No data

	Scirpus			*Typha*		
Treatment	Shoot	Root	Rhizome	Shoot	Root	Rhizome
ML	0.49	0.47	0.35	0.50	0.54	0.39
	0.38	0.56	0.40	0.58	0.33	0.36
	0.54	0.63	0.39	0.53	0.58	0.37
	0.48	0.53	0.33	0.55	0.44	0.34
MH	0.76	0.93	1.39	1.27	0.97	1.46
	0.86	1.08	1.59	1.15	1.30	1.22
	0.61	0.93	1.85	1.15	0.87	.96
	0.82	0.90	1.28	ND	0.93	1.42
SCL	0.46	0.79	0.52			
	0.46	0.74	0.48			
	0.43	0.59	0.37			
	0.40	0.69	0.39			
SCH	0.86	0.99	1.22			
	1.06	1.40	1.53			
	0.99	1/25	1.61			
	0.69	1.31	1.28			
TCL				0.61	0.35	0.34
				0.45	0.31	0.39
				0.58	0.62	0.48
				0.90	0.62	0.37
TCH				1.54	1.85	1.49
				1.29	1.19	1.29
				1.83	1.35	1.77

Table 7. Summary of plant tissue nutrient concentrations (% dry weight) and C:N:P based on seasonal sampling at the demonstration wetlands and Laguna Creek

Date	Plant Part	Total Organic Carbon			Total Kjeldahl Nitrogen			Total Phosphorous			C : N : P		
		WW Ave	Cell 5	LC	WW Ave	Cell 5	LC	WW Ave	Cell 5	LC	WW Ave	Cell 5	LC
November 1995	SA S	27.63	28.15	28.00	1.11	0.73	0.75	0.20	0.19	0.20	138:6:1	148:4:1	140:4:1
	SA R	25.67	28.20	28.23	2.11	1.17	1.14	0.32	0.21	0.19	80:7:1	134:6:1	149:6:1
	TS S	27.71	28.94	28.95	0.92	0.79	0.96	0.16	0.07	0.11	173:6:1	413:11:1	263:9:1
	TS R	28.65	29.19	16.06	1.86	0.85	1.25	0.32	0.15	0.21	90:6:1	195:6:1	76:6:1
March 1996	SA S	27.69	28.20	27.22	1.90	1.12	1.58	0.33	0.19	0.33	84:6:1	148:6:1	82:5:1
	SA R	27.96	28.14	27.91	2.60	1.84	1.38	0.40	0.28	0.21	70:7:1	101:7:1	133:7:1
	TS S	26.15	28.61	29.28	1.50	1.26	1.21	0.25	0.17	0.07	105:6:1	168:7:1	418:17:1
	TS R	28.81	29.13	29.49	2.43	1.59	0.50	0.33	0.20	0.11	87:7:1	146:8:1	268:5:1
May 1996	SA S	27.17	27.00	27.67	1.75	1.34	1.13	0.26	0.20	0.25	104:7:1	135:7:1	111:4:1
	SA R	27.98	28.22	28.32	2.06	1.47	1.28	0.33	0.24	0.36	85:6:1	118:6:1	79:4:1
	TS S	27.02	24.65	26.92	1.77	1.84	1.05	0.26	0.23	0.17	104:7:1	107:8:1	158:6:1
	TS R	27.13	27.75	27.33	3.14	1.77	1.41	0.45	0.33	0.26	60:7:1	84:5:1	105:5:1

WW = Average of all wastewater treatment cells sampled
LC = Laguna Creek
SA S = *Scirpus acutus* shoots
SA R = *Scirpus acutus* rhizomes
TS S = *Typha* spp. leaves
TS R = *Typha* spp. rhizomes

Table 8. T-test results on comparisons of regression equations of transformed data from litterbags suspended in the watercolumn. Species (S-Scirpus, T-Typha)

Species & Location	t value	df	Significance
S1A, S1B	-3.408	32	0.01 *
S5A, S5B	0.798	32	0.50 *
S7A, S7B	-2.907	30	0.01 *
SLC3, SLC4	-2.014	28	0.10 *
S5, S7	-3.059	66	0.01 *
T1A, T1B	-1.683	27	0.20 *
T5A, T5B	1.025	26	0.4 0*
T7A, T7B	-1.763	32	0.10 *
TLC3, TLC4	0.589	30	ns
T5, T7	-2.215	62	0.05 *
S1, T1	0.238	63	ns
S5, T5	-0.75	62	0.50 *
S7, T7	0.0025	66	ns
SLC, TLC	-2.938	62	0.01 *

Table 9. T-test results on comparisons of regression equations of transformed data from buried litterbags. Species (S-Scirpus rhizomes, T-Typha rhizomes and TB-Typha base).

Species & Location	t value	df	Significance
S5A, S5B	-1.001	8	0.5 *
S7A, S7B	1.478	8	0.3*
S5, S7	0.493	20	ns
S5, SLC	0.703	14	0.5*
S5A, S7A	-1.117	8	0.3 *
S5B, S7B	1.335	8	0.3 *
T5A, T5B	-0.345	8	ns
T7A, T7B	0.307	8	ns
T5, T7	0.318	20	ns
T5, TLC	-0.289	14	ns
S1A, T1A	0.907	8	0.4 *
S5, T5	2.057	20	0.05 *
S7, T7	1.441	20	0.2 *
SLC, TLC	0.668	8	ns
TB5A, TB7A	-0.318	8	ns
TB5A, T5A	0.579	8	ns
TB7A, T7A	0.614	8	ns

Table 10. T-test results on comparisons of regression equations of transformed data from litterbags suspended in the watercolumn and those buried in the same location. S-Scirpus, T-Typha, W-Water column, R-Rhizomes

Species & Location	t value	df	Significance
SW5, SR5	-1.221	44	0.3 *
SW7, SR7	1.364	42	0.2 *
TW5, TR5	2.909	38	0.01 *
TW7, TR7	0.759	44	0.001 *

Table 11. Species percent cover for transects of various water depths (10-80 cm) Deep Average (50-80 cm), Shallow Average (10-40 cm). Sampled November 1995

	Percent Cover			
Depth (cm)	*Scirpus acutus*	*Scirpus californicus*	*Typha domingensis*	Open Water
80	6.5	54.8	29.0	9.7
70	22.6	48.4	22.6	6.5
60	25.8	48.4	19.4	6.5
50	38.7	22.6	25.8	12.9
40	41.9	16.1	29.0	12.9
30	19.4	61.3	19.4	0.0
20	38.7	35.5	16.1	9.7
10	54.8	6.5	29.0	9.7
Deep Ave	23.4	43.5	24.2	8.9
Shallow Ave	38.7	29.8	23.4	8.1
Total Ave	31.0	36.7	23.8	8.5

Table 12. Average concentrations (mg/kg) of total carbon (TC), total kjeldahl nitrogen (TKN) and total phosphorous (TP) in sediment of cells 5 and 7 along the distance gradient of inflow to outflow.
1996 values

Constituent Cell #	TC 5	TC 7	TKN 5	TKN 7	TP 5	TP 7
Distance meters						
0	6385	6825	585	1220	82	190
30	11050	11865	725	855	55	185
55	12850	8045	900	970	170	165
76	12205	8045	845	1085	335	132
128	8645	8655	830	1450	325	155
171	11975	19005	1045	1050	235	185
241	8130	8550	500	960	145	171
329	12100	9555	915	1100	72	110
Average	10417.50	10068.13	793.13	1086.25	177.38	161.63
Standard Deviation	2372.59	3898.08	180.34	183.08	110.99	28.24

C:N:P Cell 5 59:4:1
C:N:P Cell 7 62:7:1

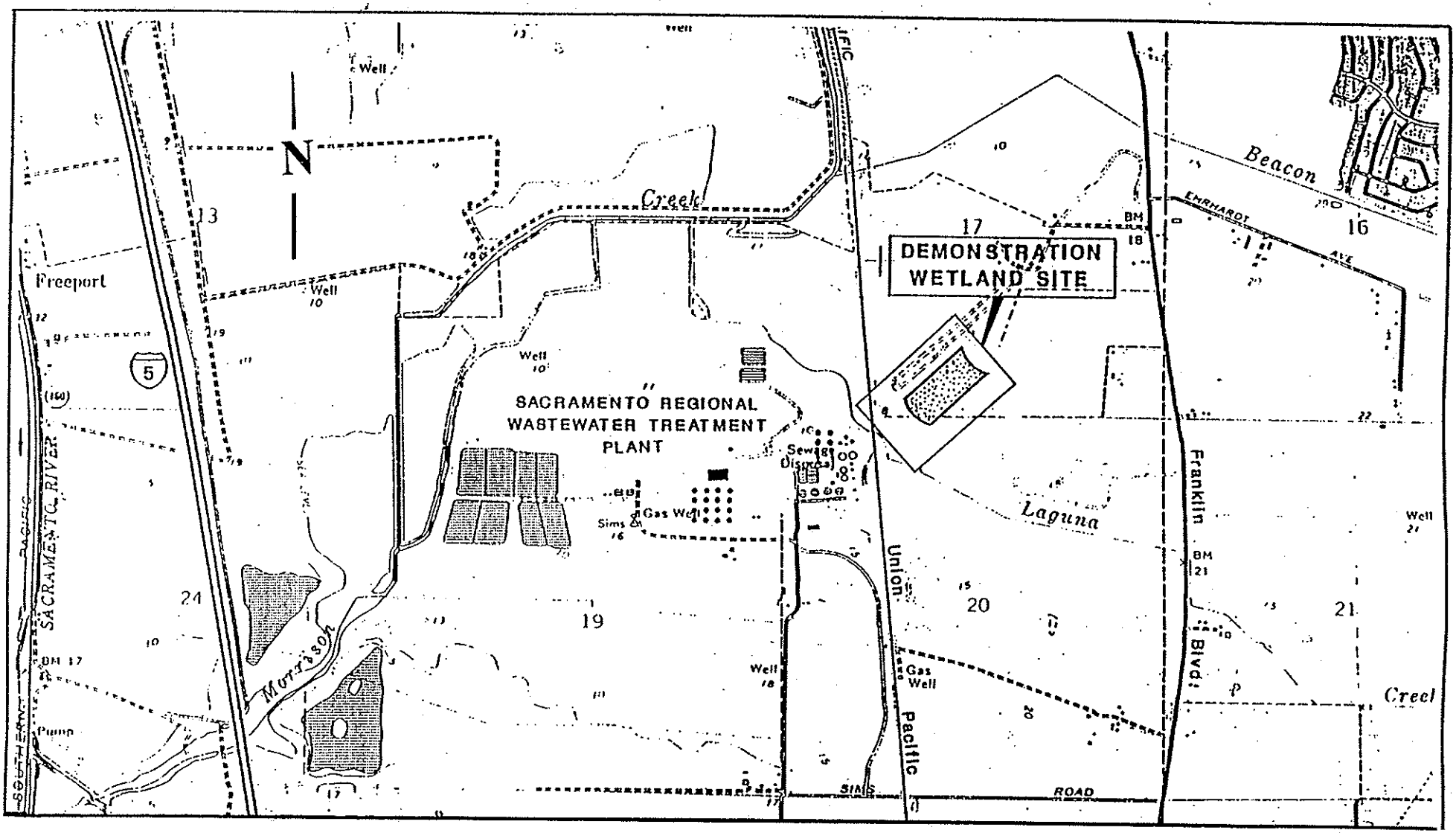

Figure 1. Location of the constructed wetlands on the bufferland property of Sacramento Regional Wastewater Treatment Plant in Elk Grove, California.

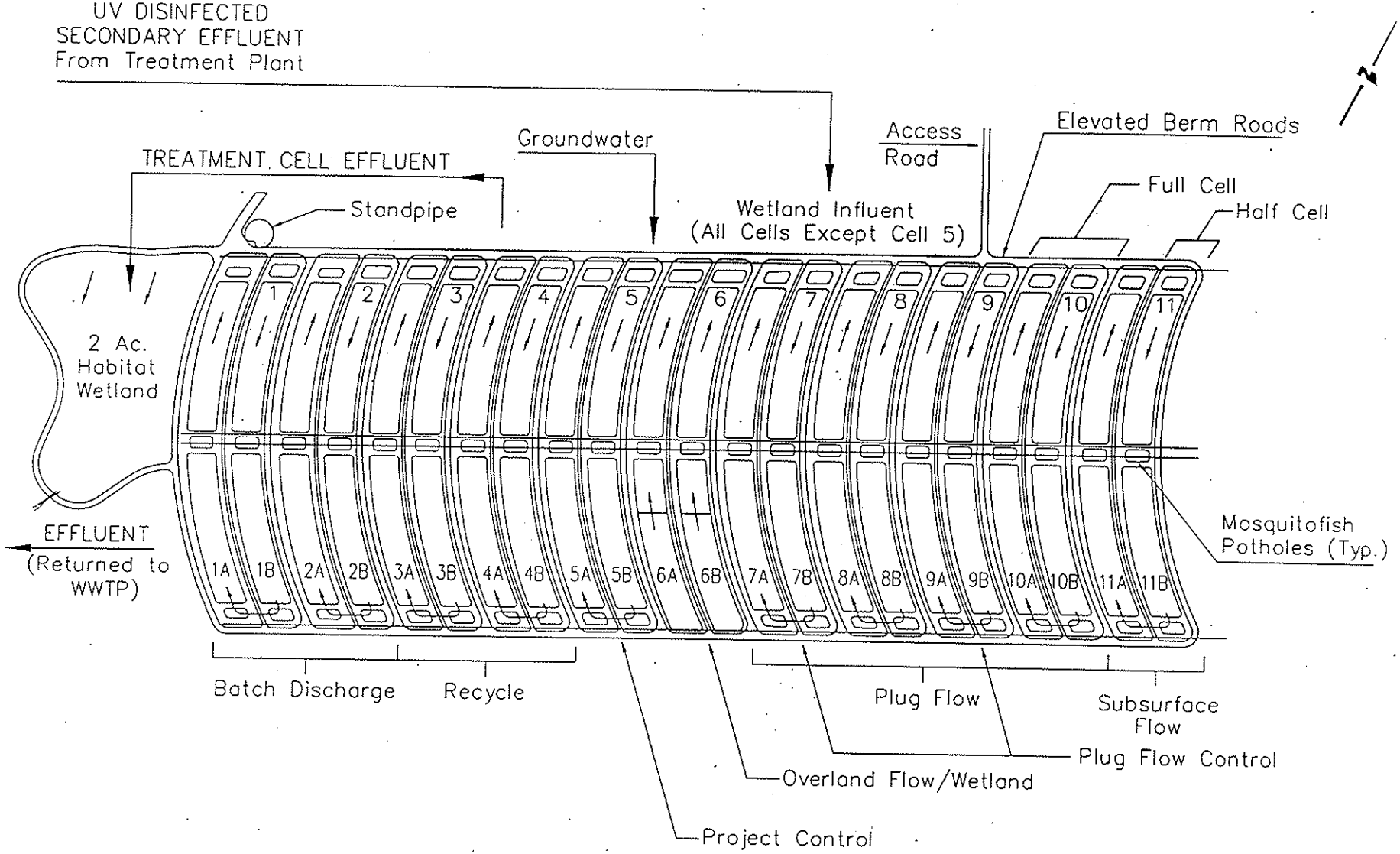

Figure 2. Sacramento demonstration wetland conceptual design

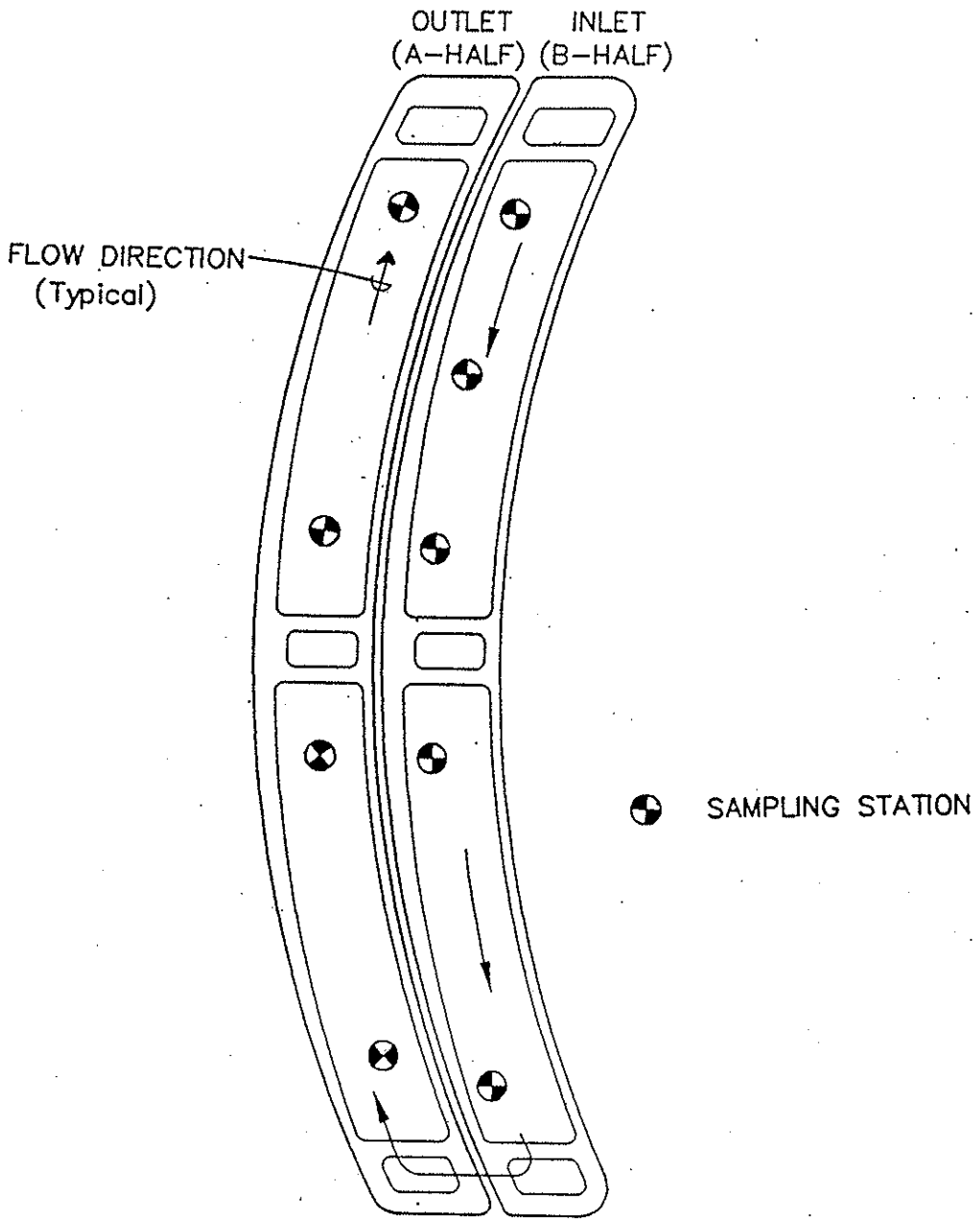

Figure 3. Location of sampling quadrats in cells 1, 5 and 7.

North

SA	TD	SC	SA	TD	SC	SA	TD	SC	TD	SC	SA	TD	SA	SC
SC	SA	TD	SC	SA	TD	SC	SA	TD	SA	TD	SC	SA	SC	TD
TD	SC	SA	TD	SC	SA	TD	SC	SA	SC	SA	TD	SC	TD	SA
SC	TD	SA	SA	TD	SC	SA	SC	TD	SC	SA	TD	SC	TD	SA
TD	SA	SC	TD	SC	SA	TD	SA	SC	TD	SC	SA	TD	SA	SC
SA	SC	TD	SC	SA	TD	SC	TD	SA	SA	TD	SC	SA	SC	TD

Fig. 4. Initial planting design for water depth competition study.

Note:

SA *Scirpus acutus*
SC *Scirpus californicus*
TD *Typha domingensis*

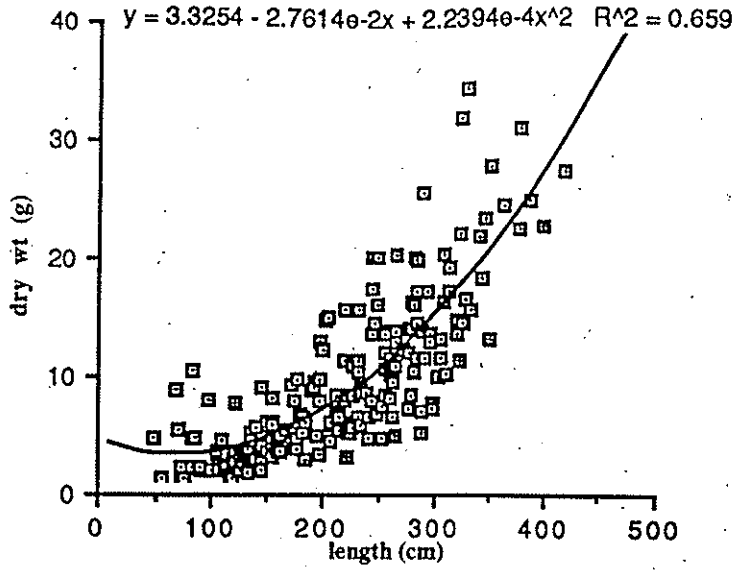

Fig 5. SA dry weight as a function of plant height (1994).

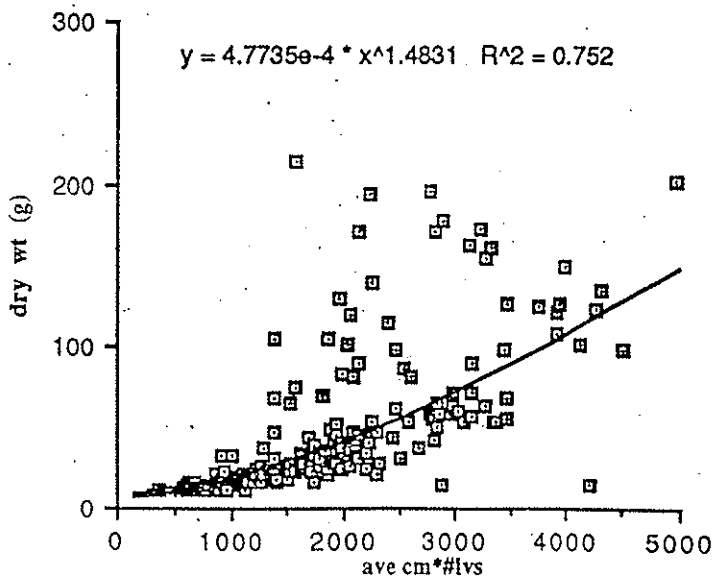

Fig. 6. TD dry weight as a function of plant height and number of plant leaves (1994).

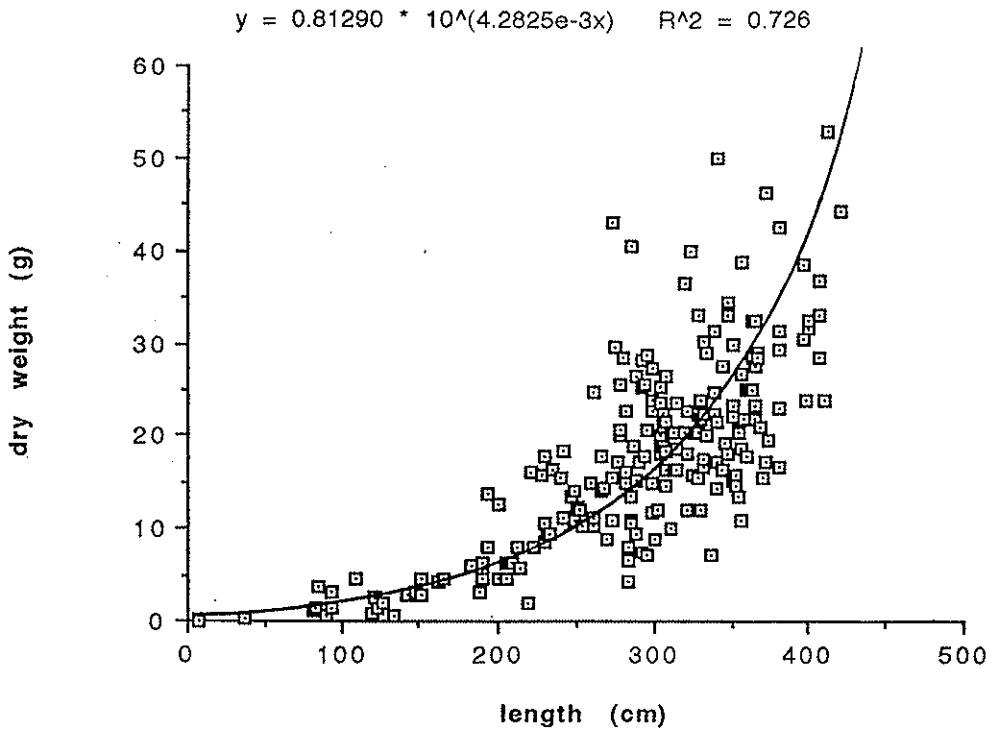

Fig. 7. SA dry weight as a function of plant height (1996)

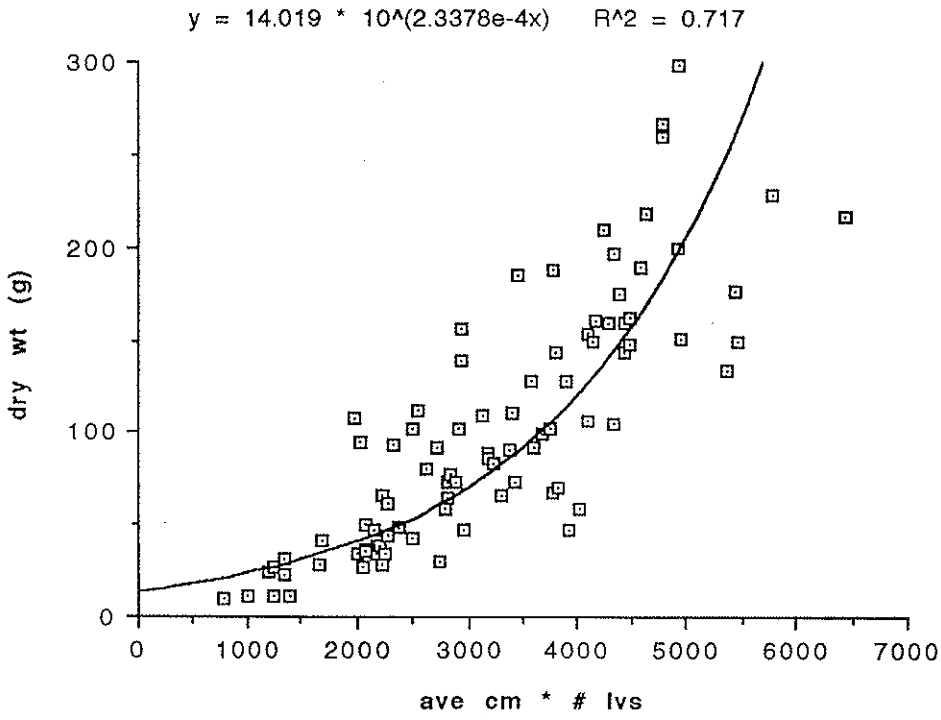

Fig. 8. TD dry weight as a function of plant height and number of leaves (1996)

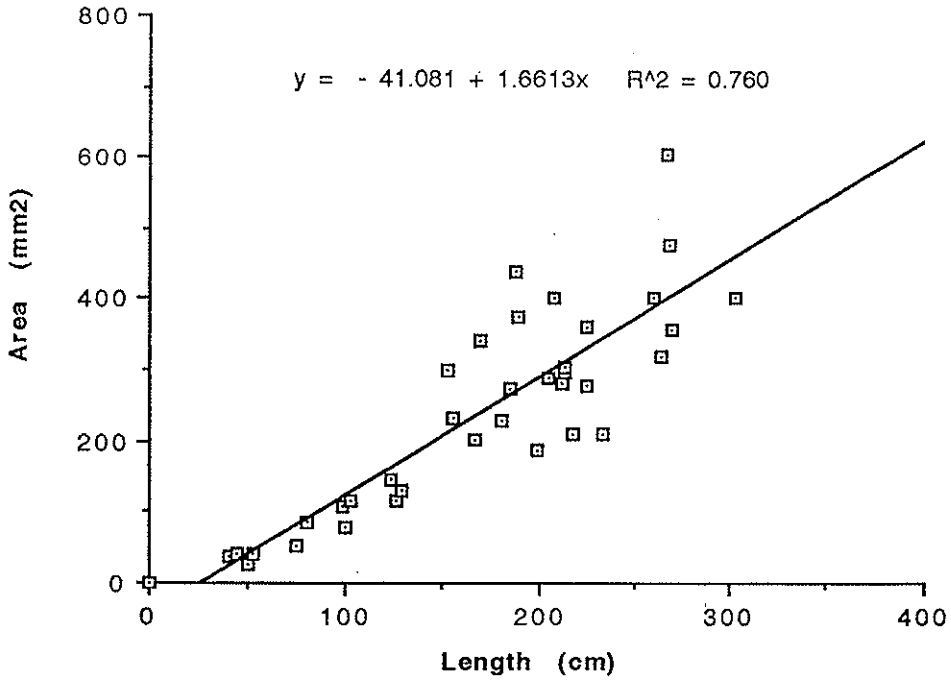

Fig. 9. SA leaf area as a function of shoot length

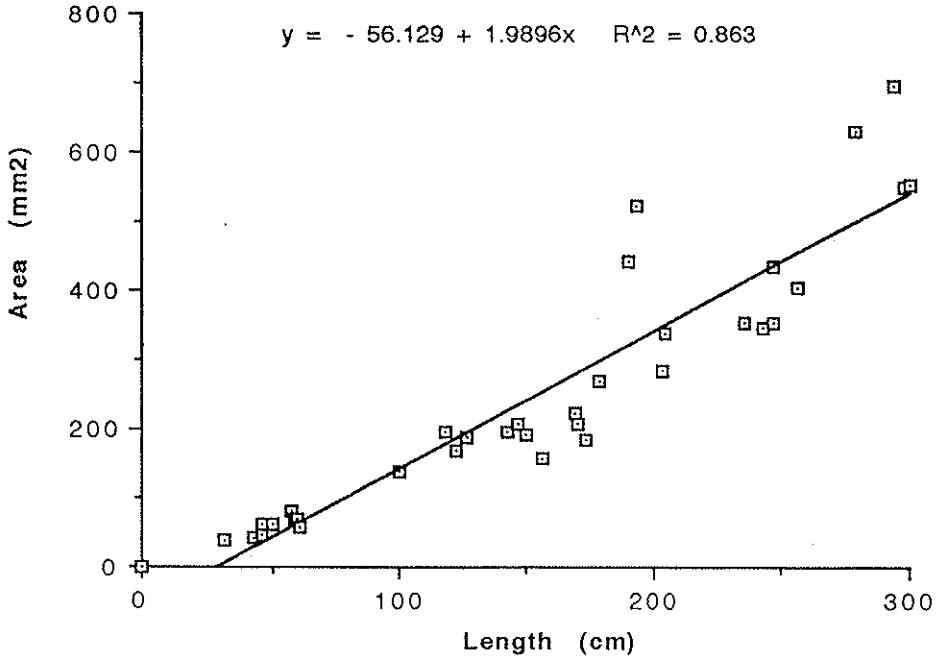

Fig. 10. TS leaf area as a function of leaf length

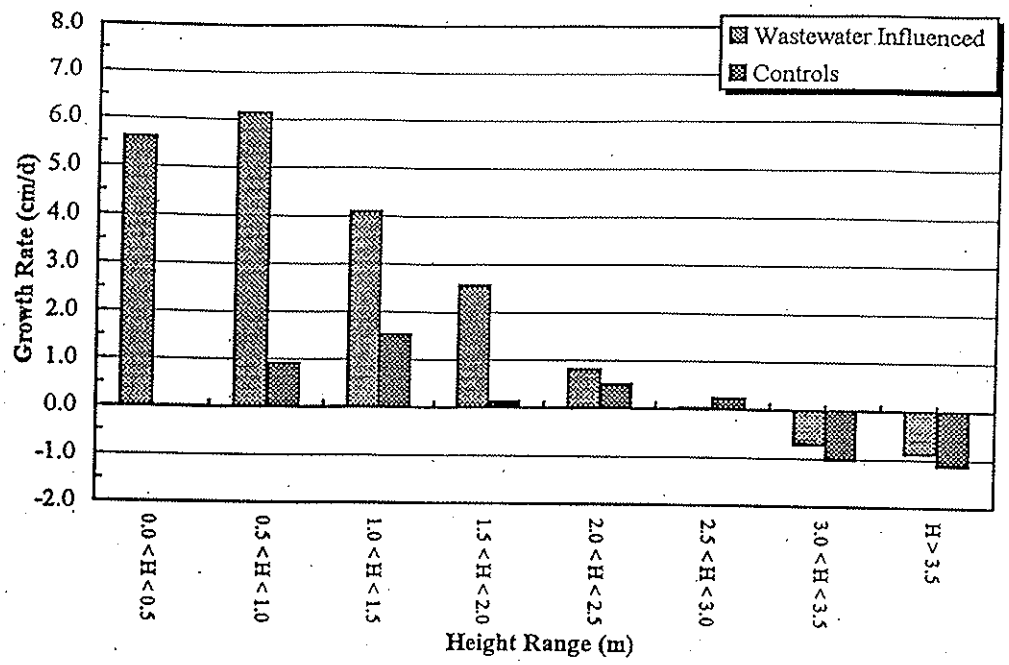

Fig. 11. Comparison of average SA growth rates in wastewater influenced cells and controls

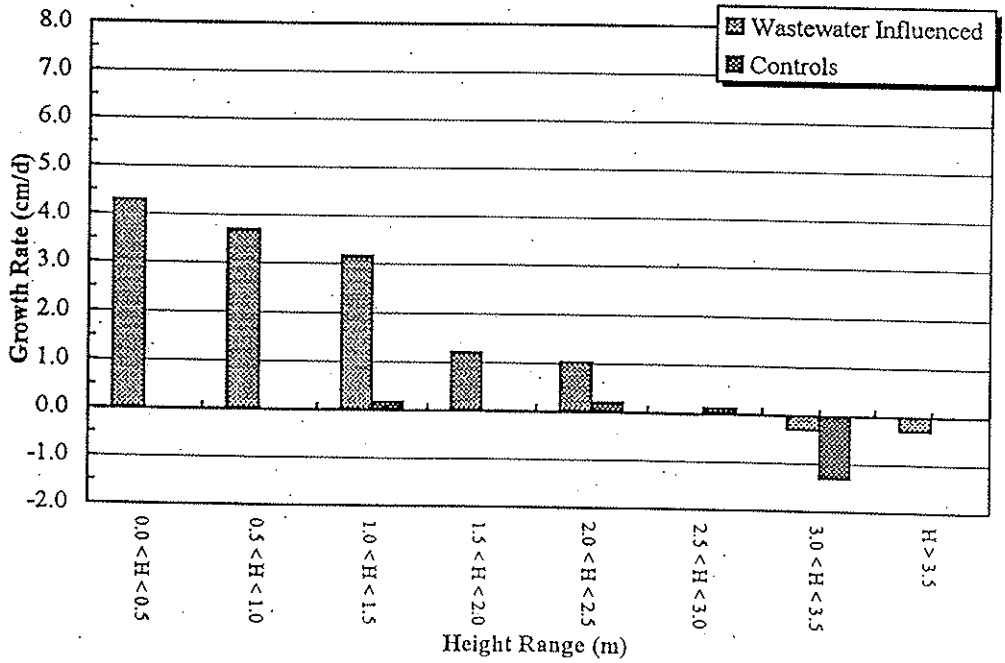

Fig. 12. Comparison of average TS growth rates in wastewater influenced cells and controls

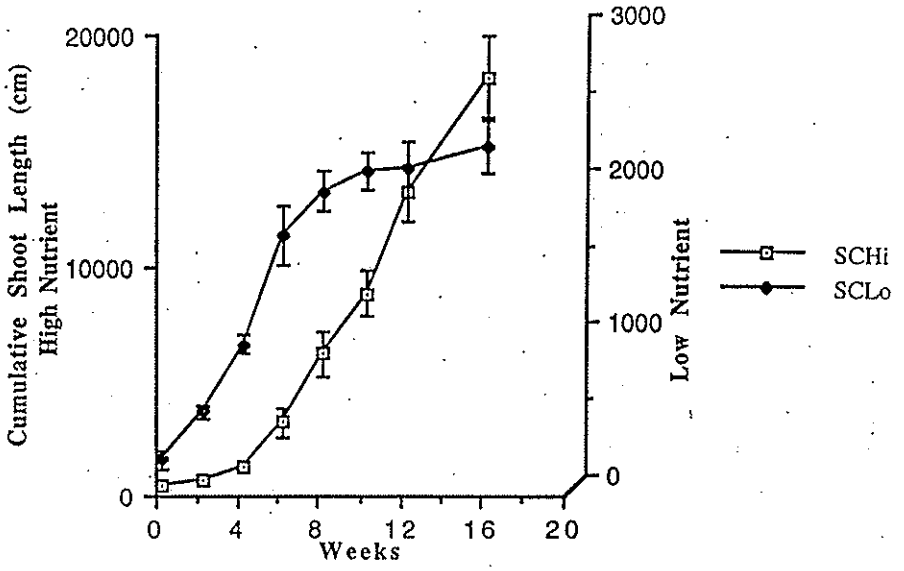

Fig. 13. Cumulative shoot lengths in SA monocultures

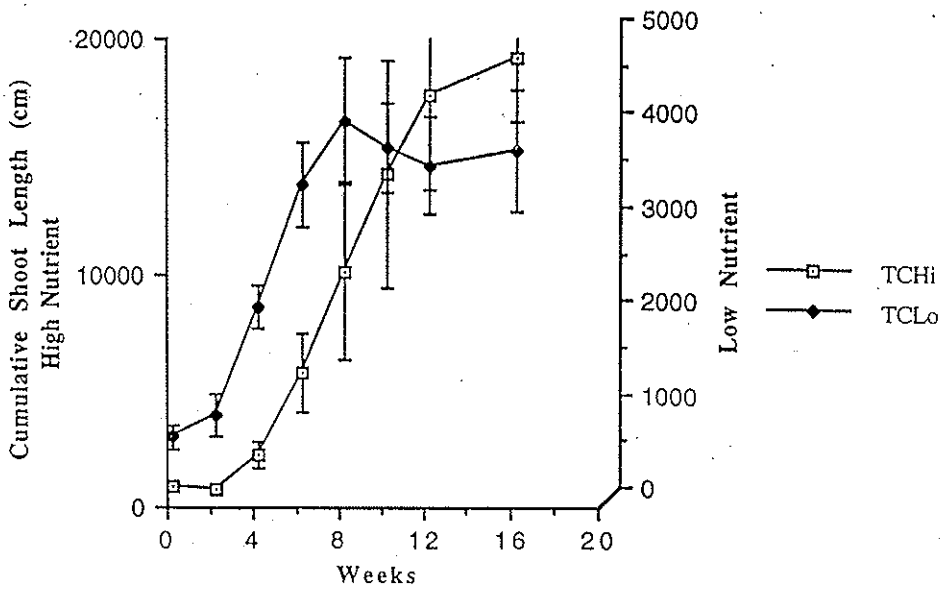

Fig. 14. Cumulative shoot lengths in TD monocultures

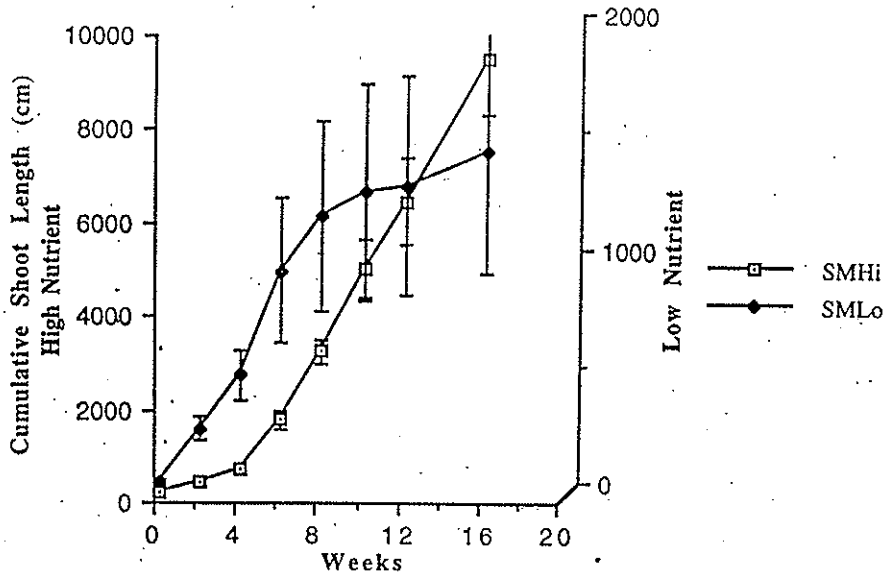

Fig. 15 Cumulative shoot lengths for SA in mixed cultures

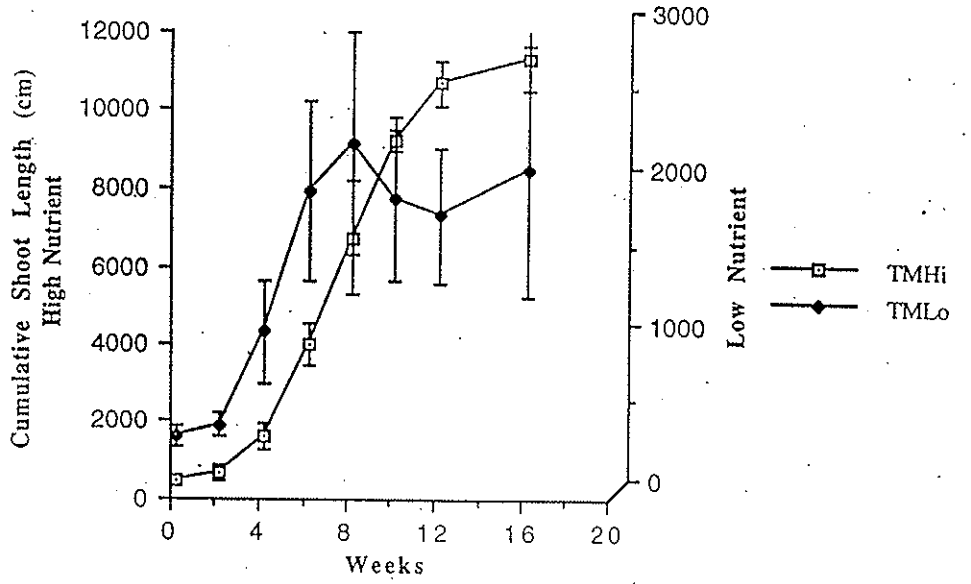

Fig. 16. Cumulative shoot lengths for TD in mixed cultures

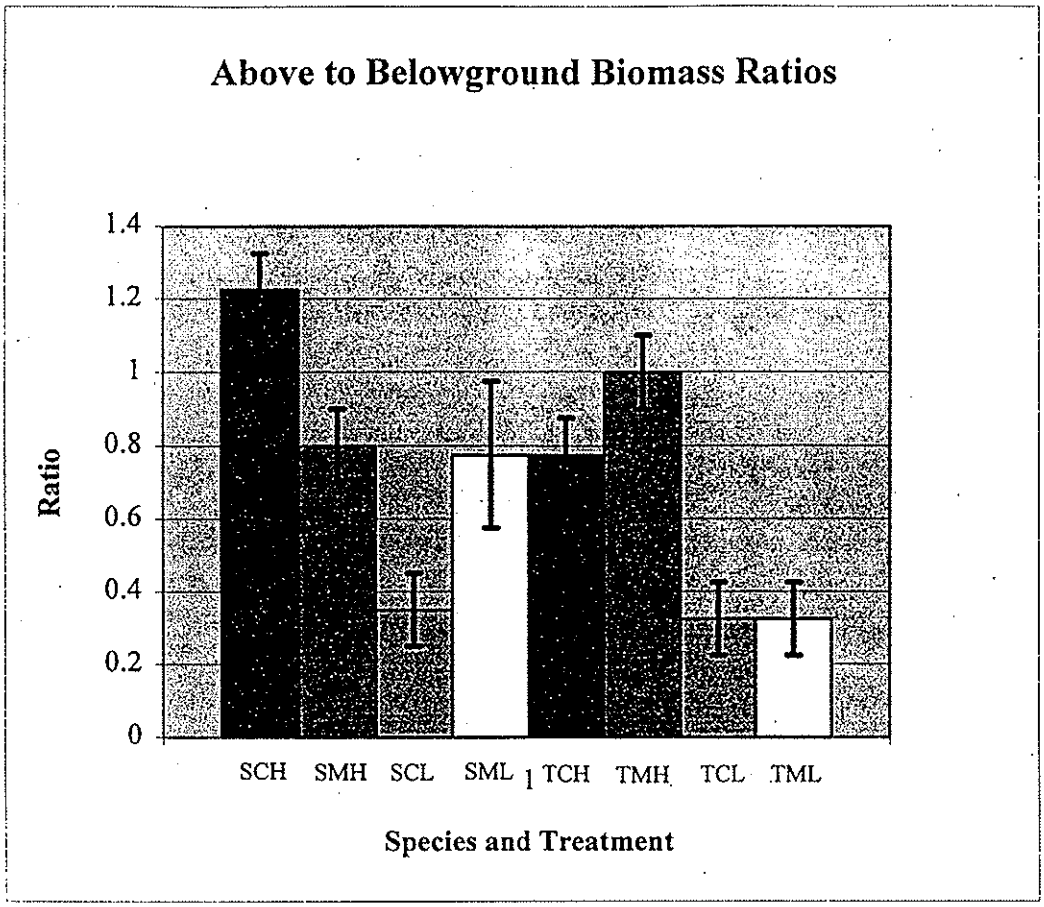

Fig. 17. Above to below ground biomass ratios for SA and TD in mesocosms. S=Scirpus; T=Typha; M=Mixed cultures; C=Monocultures; H=High nutrient; L=Low nutrient

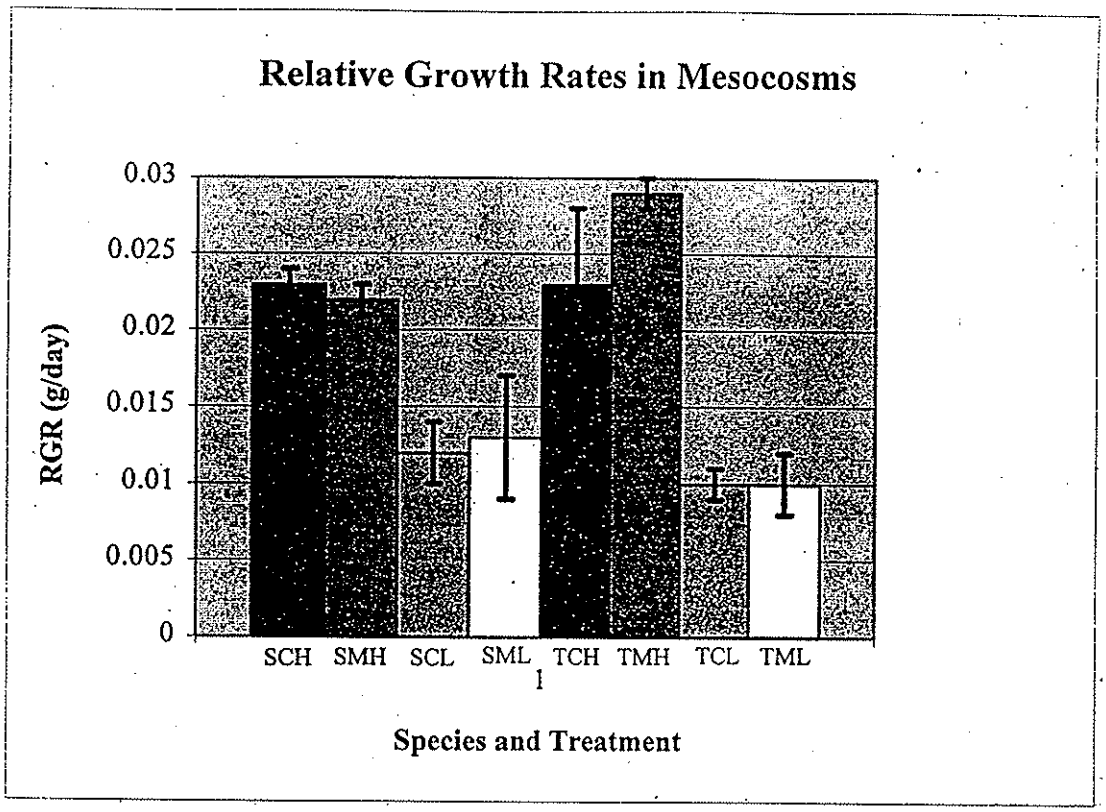

Figure 18. Relative growth rates for SA and TS in mesocosms. S=Scirpus; T=Typha; M=Mixed cultures; C=Monoculture; H=High nutrient; L=Low nutrient

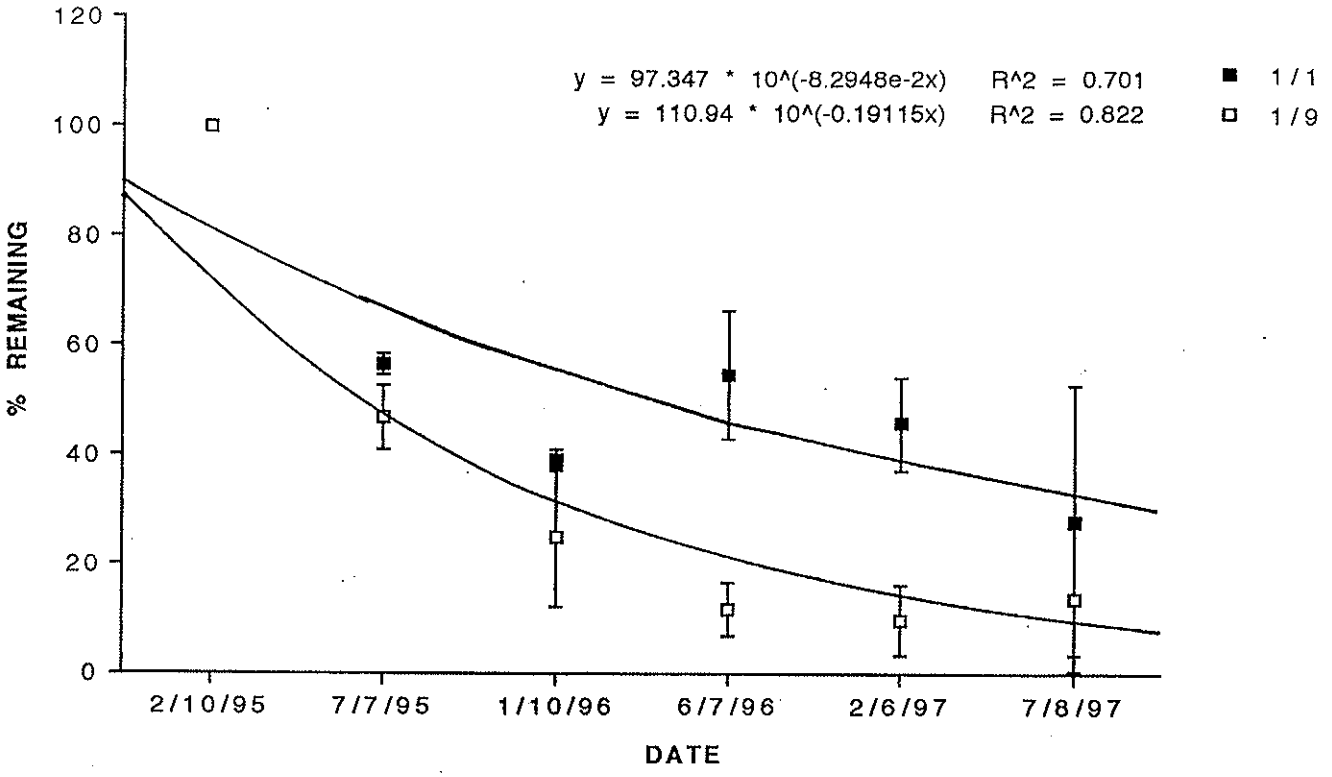

Fig. 19. Decomposition of SA litter in the water column of cell 1.

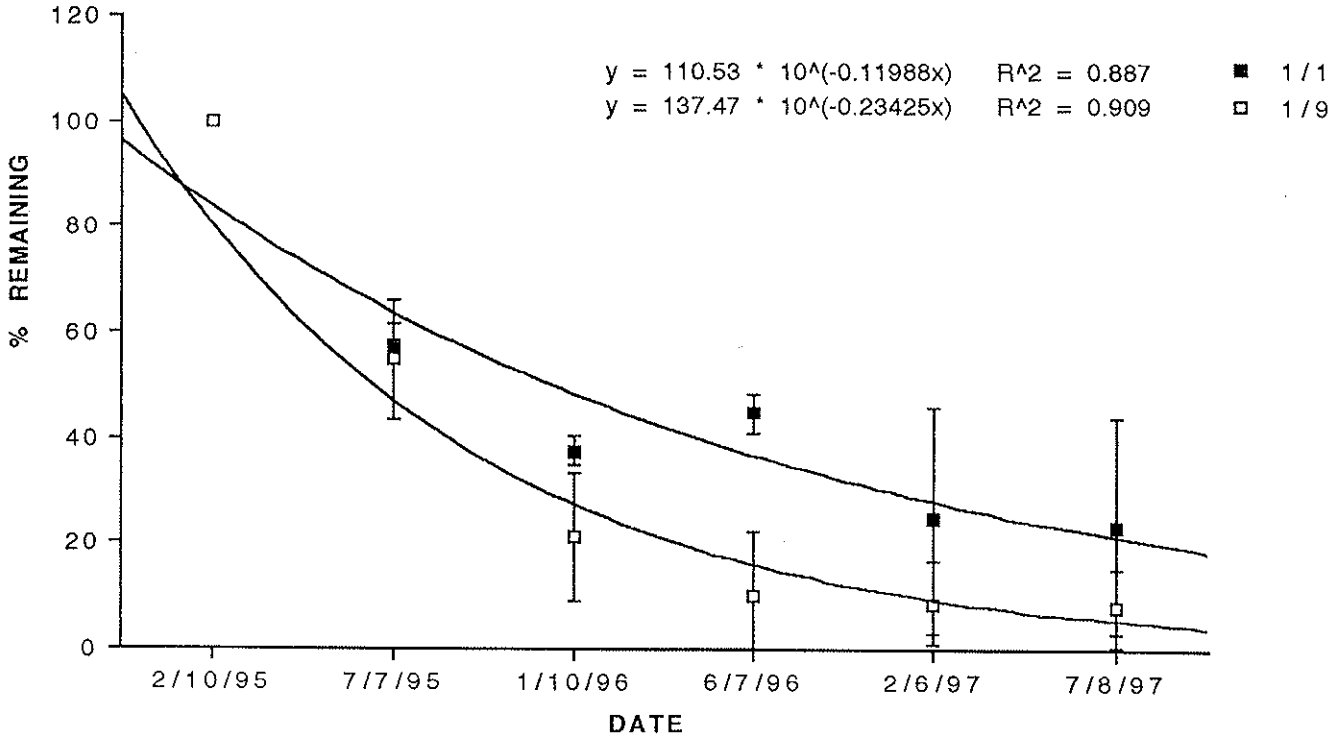

Fig. 20. Decomposition of TS litter in the water column of cell 1

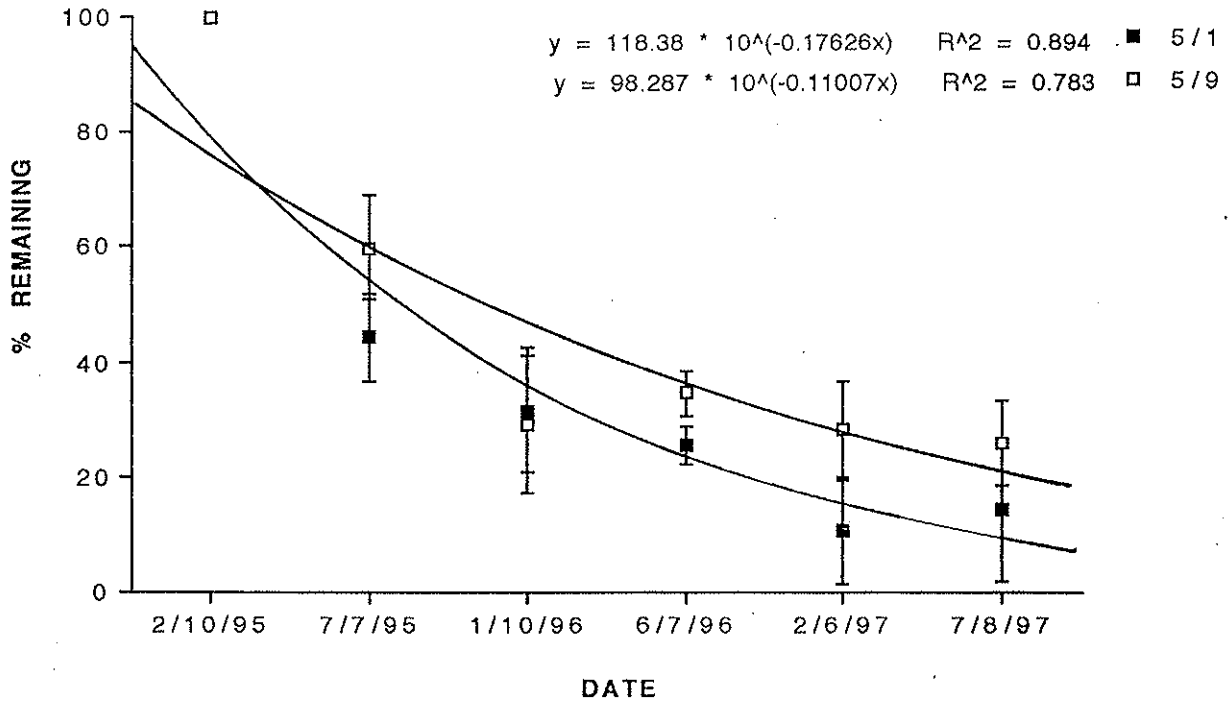

Fig. 21. Decomposition of SA litter in the water column of cell 5

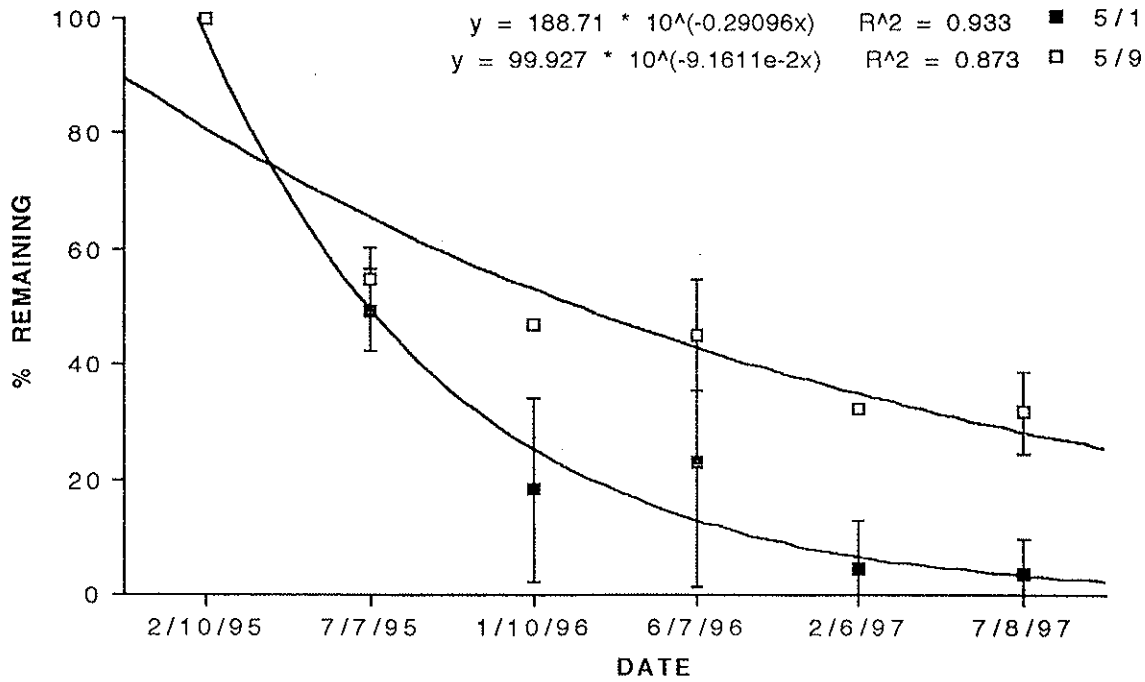

Fig. 22. Decomposition of TS litter in the water column of cell 5

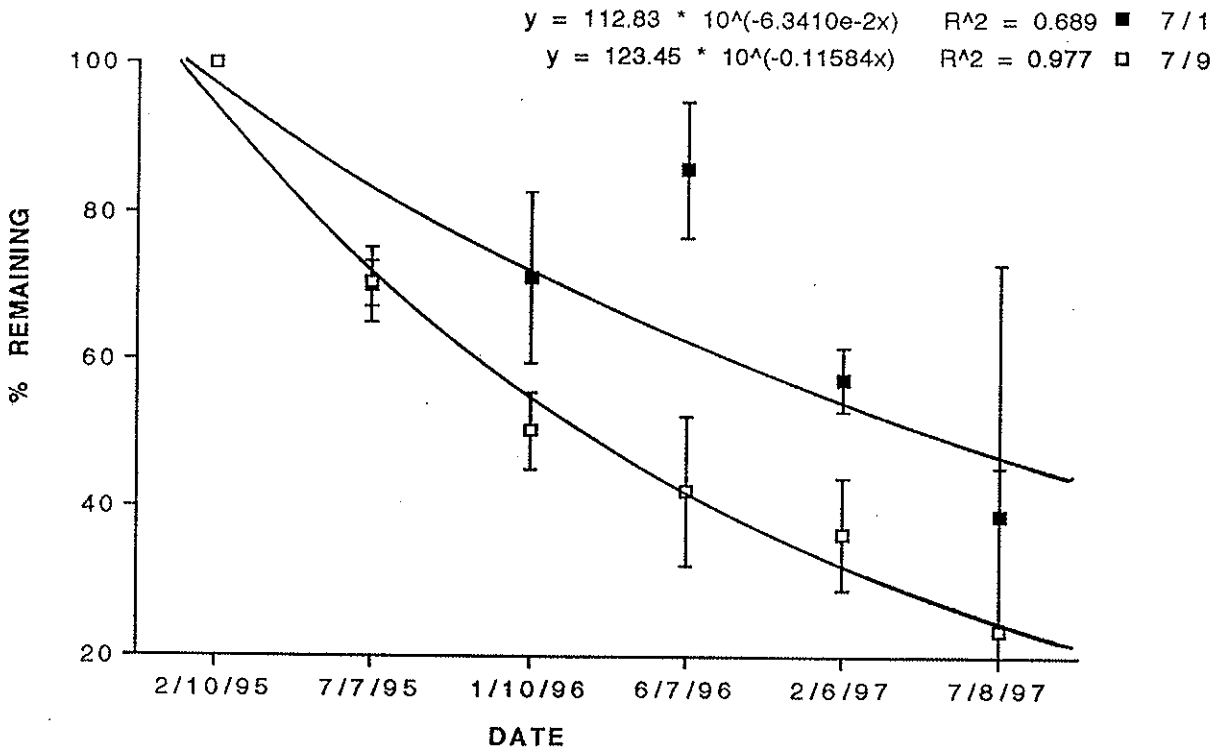

Fig. 23. Decomposition of SA litter in the water column of cell 7

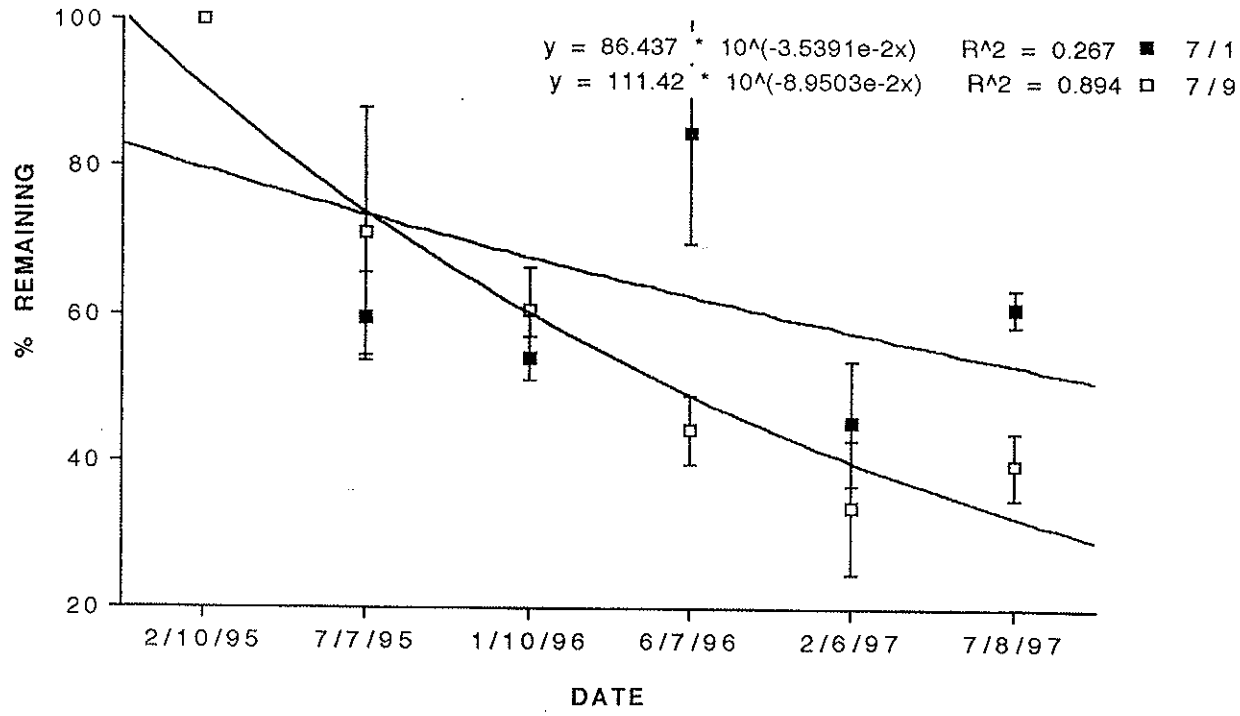

Fig. 24. Decomposition of TS litter in the water column of cell 7

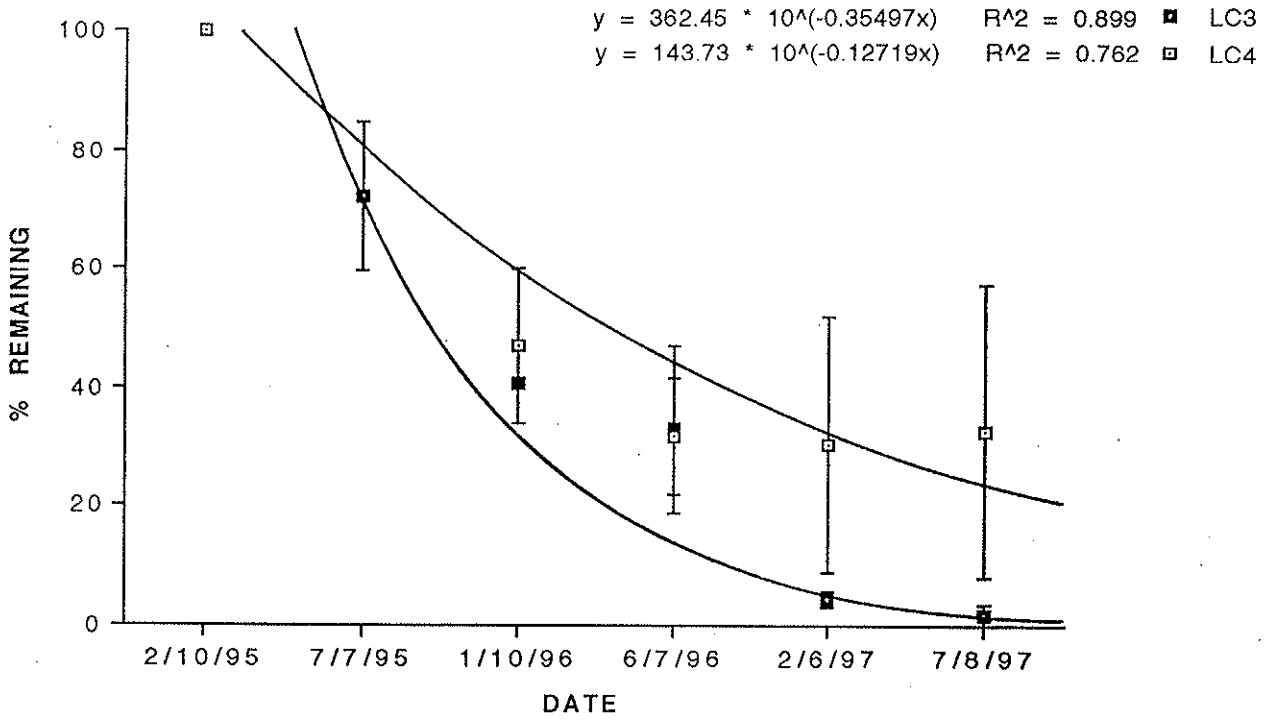

Fig. 25. Decomposition of SA litter in the water column of Laguna Creek

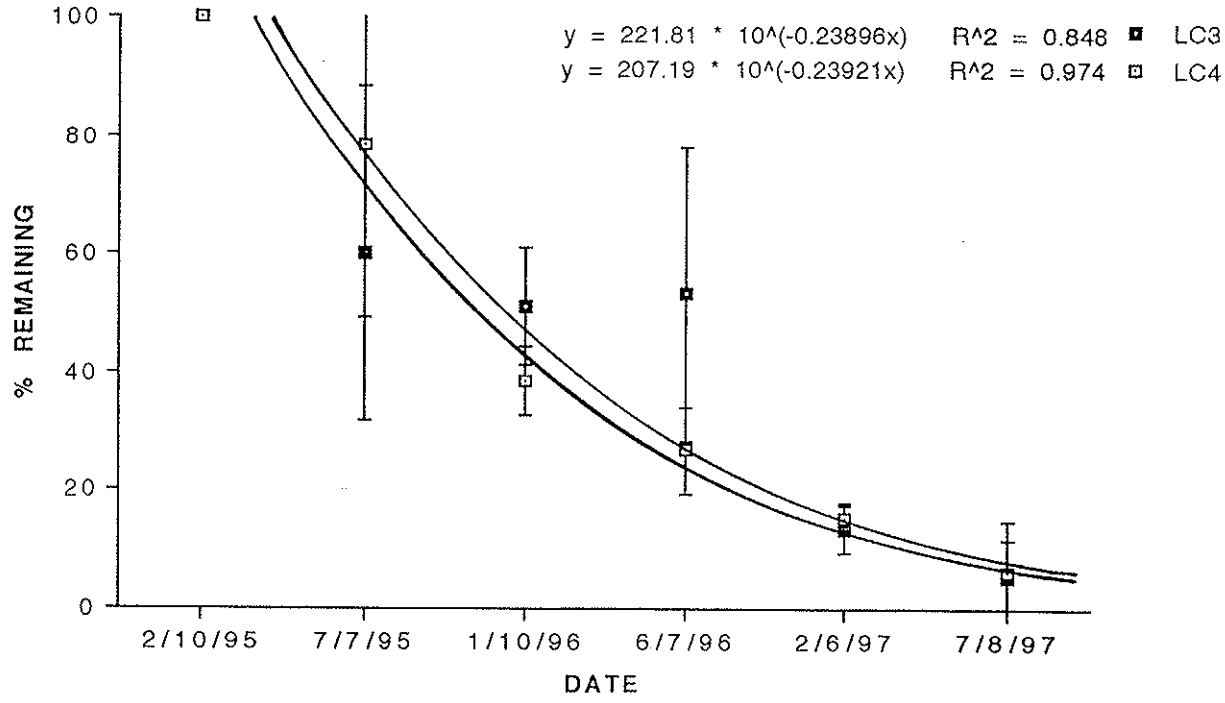

Fig. 26. Decomposition of TS litter in the water column of Laguna Creek

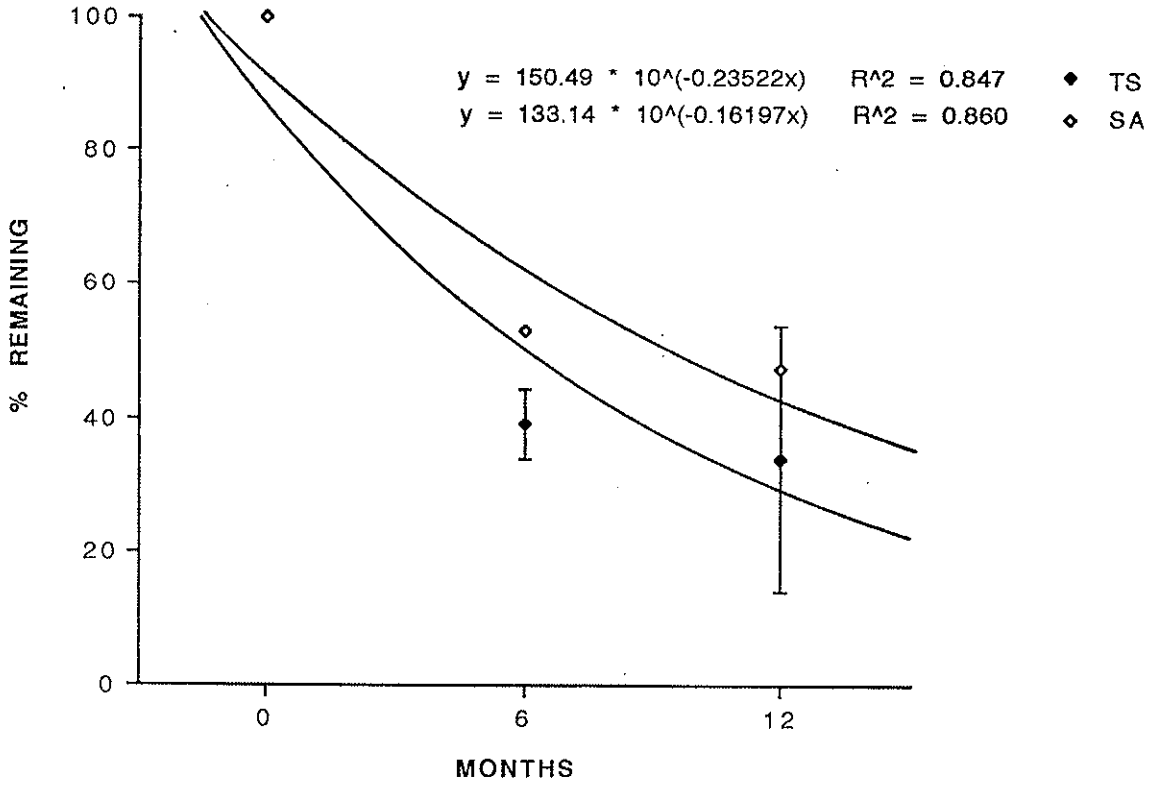

Fig. 27. Decomposition of SA and TS buried rhizomes in cell 1A

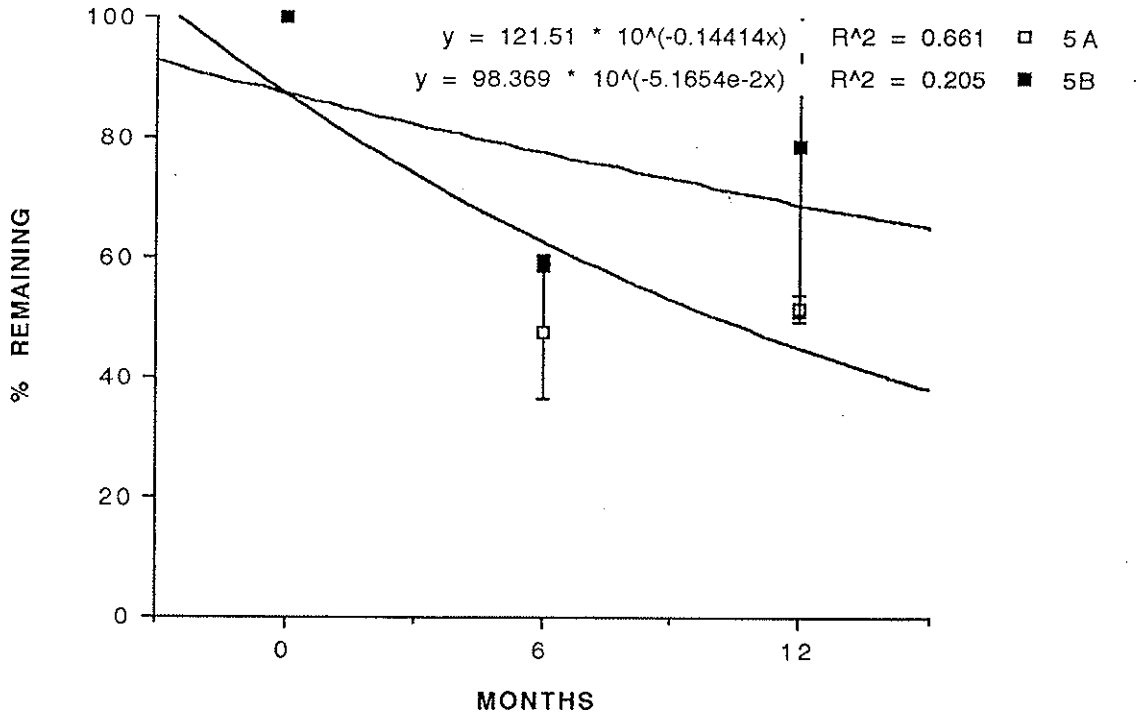

Fig. 28. Decomposition of buried SA rhizomes in cell 5

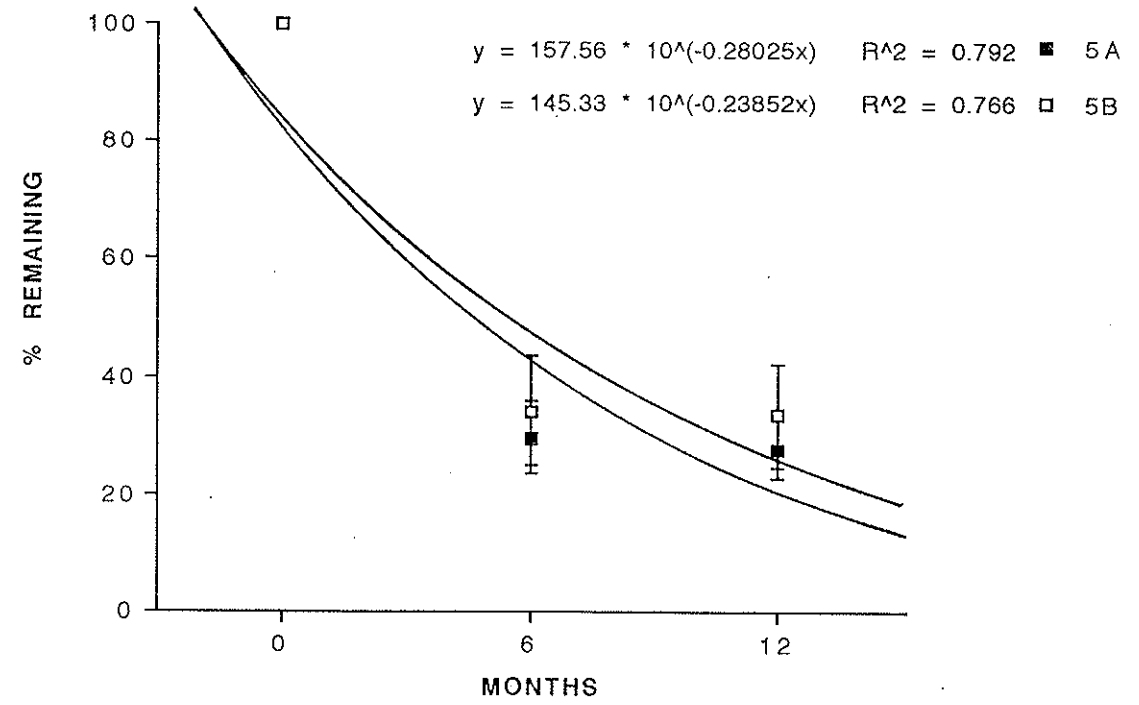

Fig. 29. Decomposition of buried TS rhizomes in cell 5

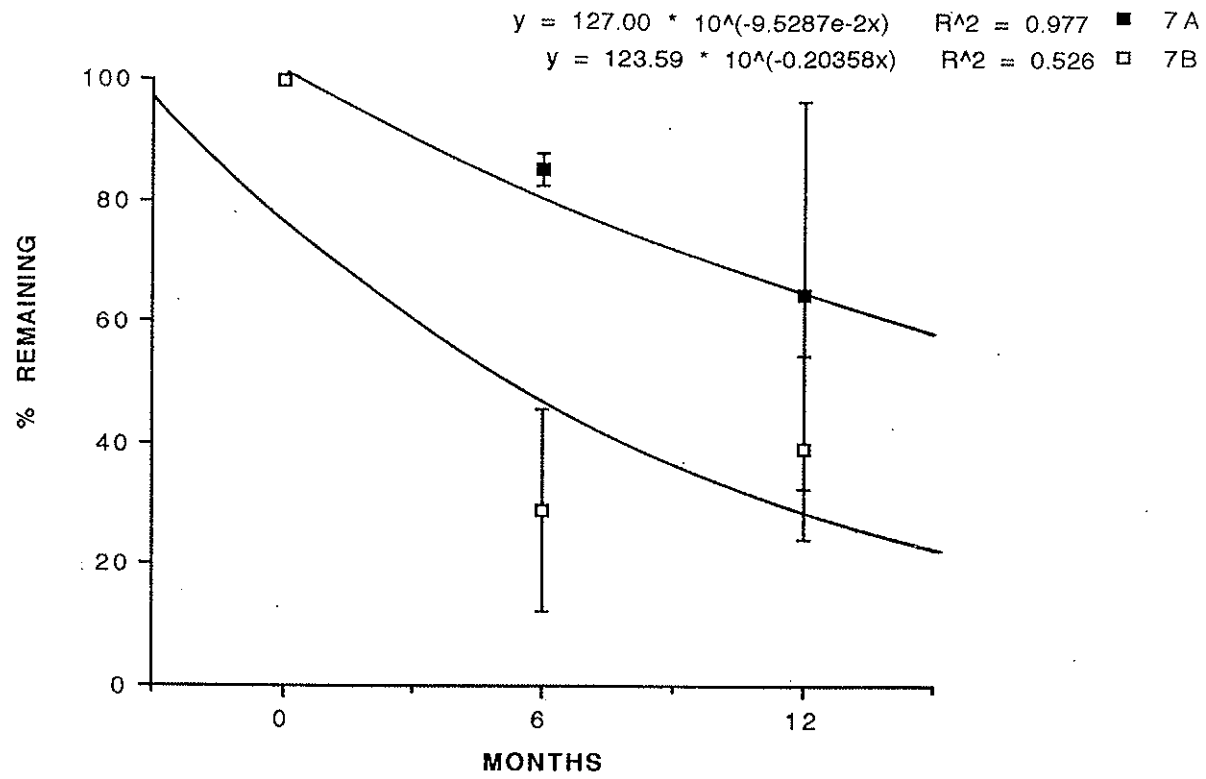

Fig. 30. Decomposition of buried SA rhizomes in cell 7

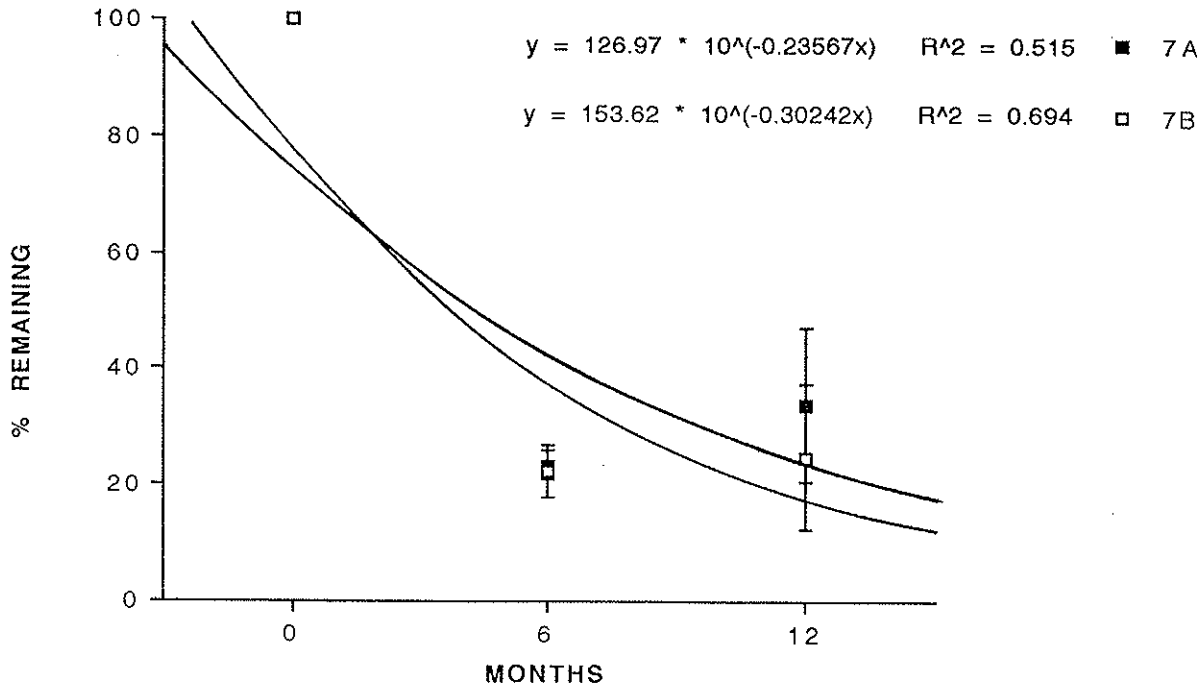

Fig. 31. Decomposition of buried TS rhizomes in cell 7

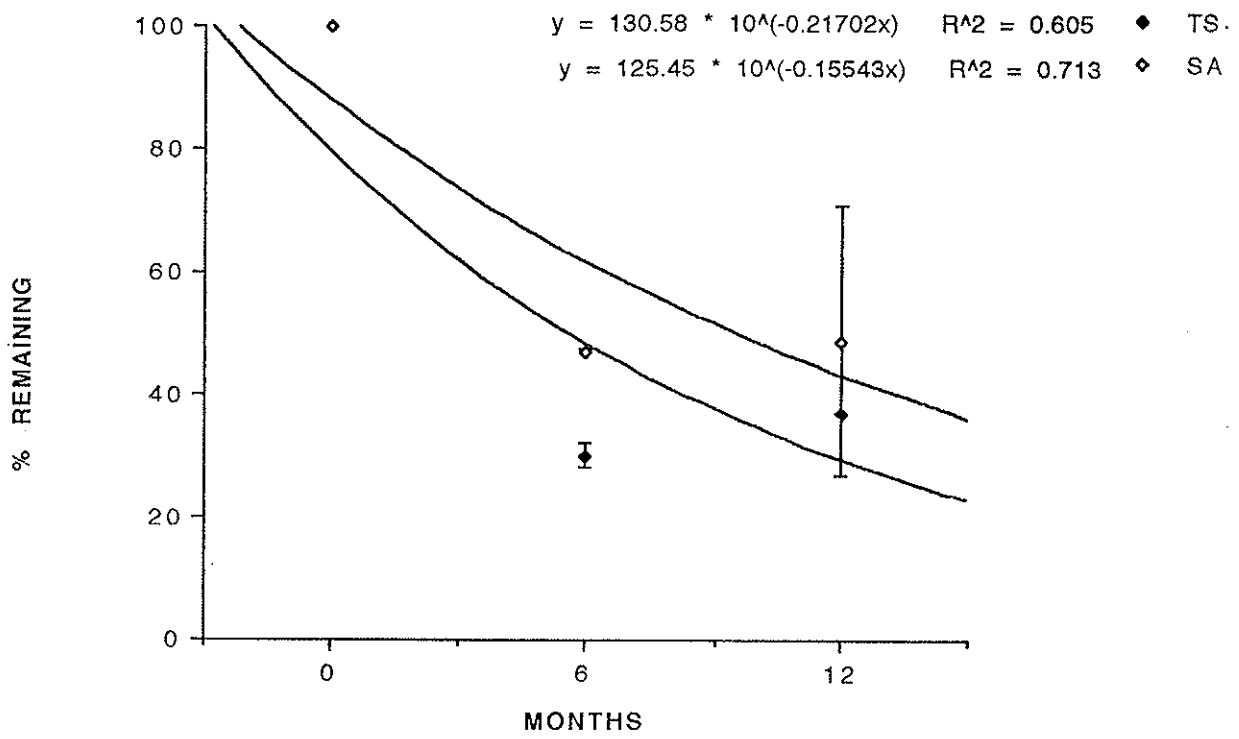

Fig. 32. Decomposition of buried SA and TS rhizomes in Laguna Creek

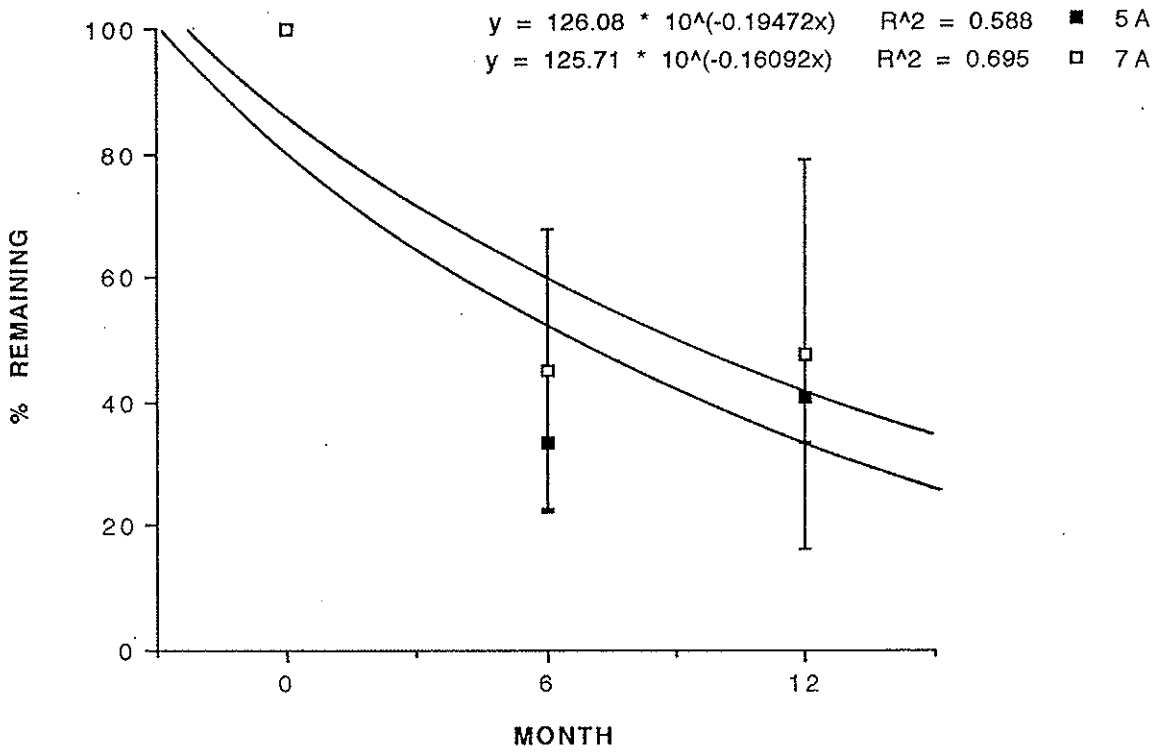

Fig. 33. Decomposition of buried TS bases in cells 5A & 7A

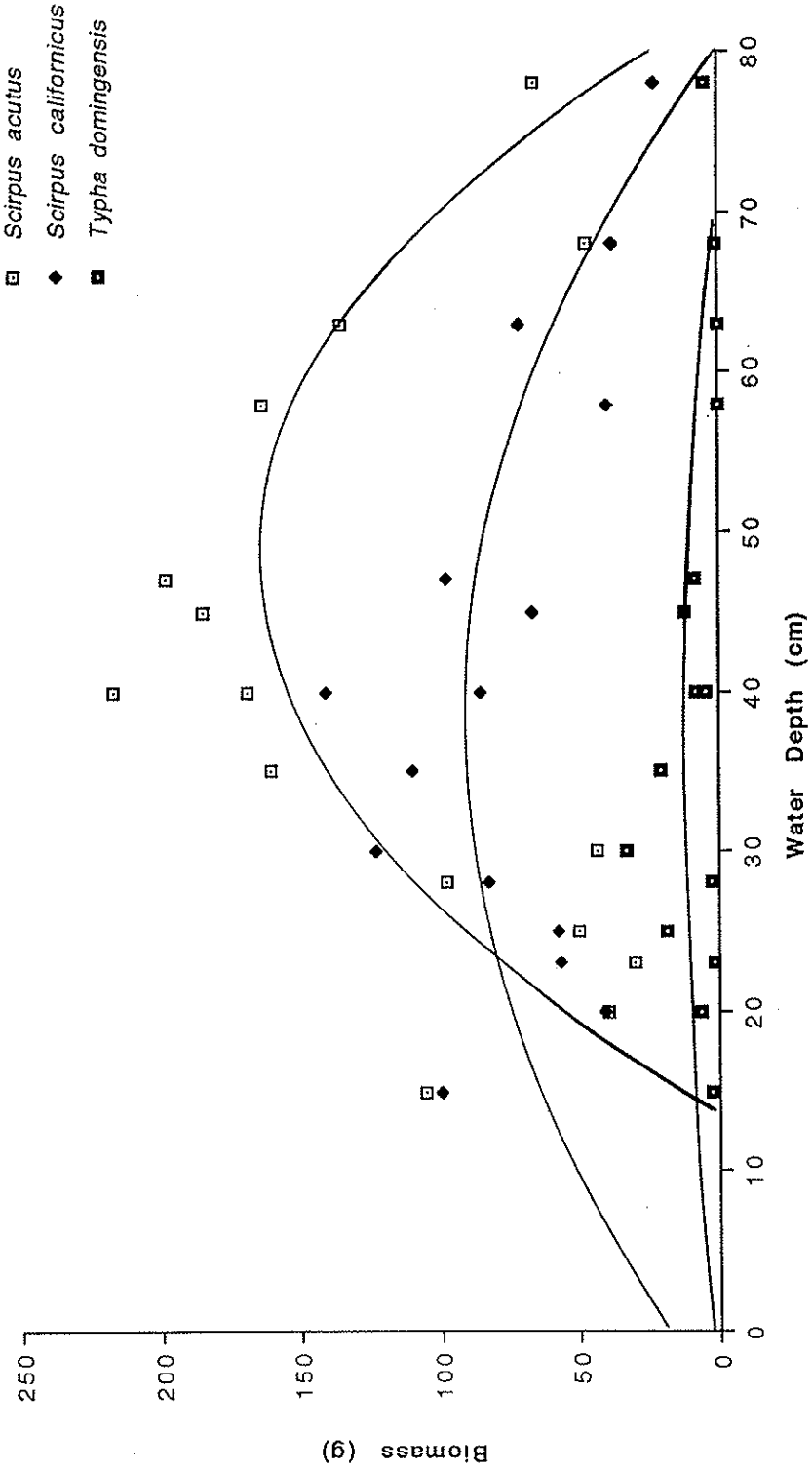

Fig. 34. Plant biomass at various water depths. September 1994

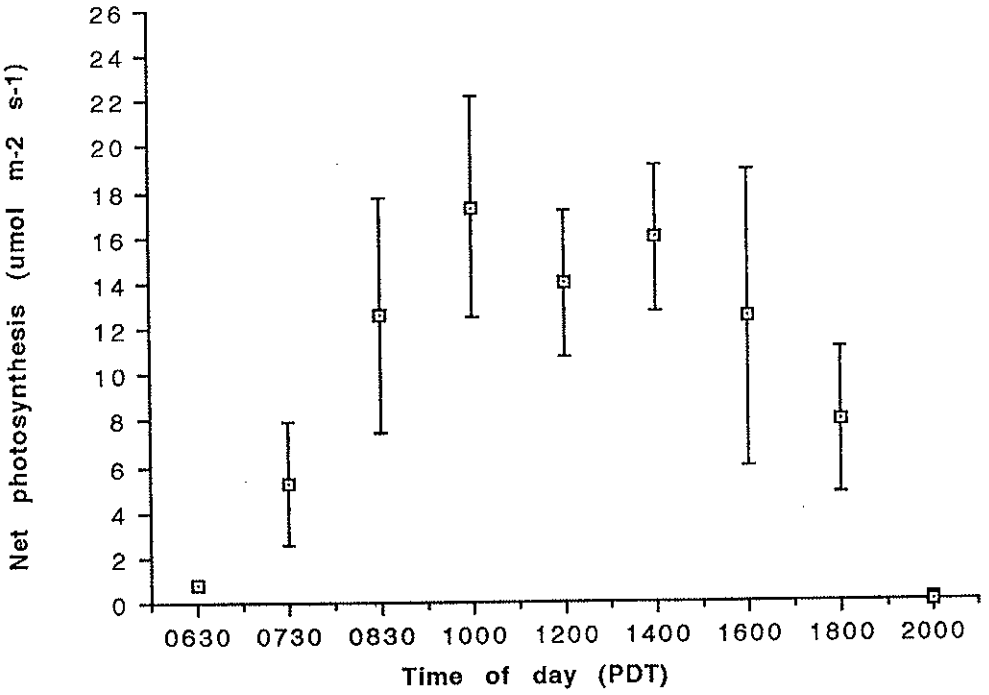

Fig. 35. Diurnal course of net photosynthesis for SA on August 4, 1995

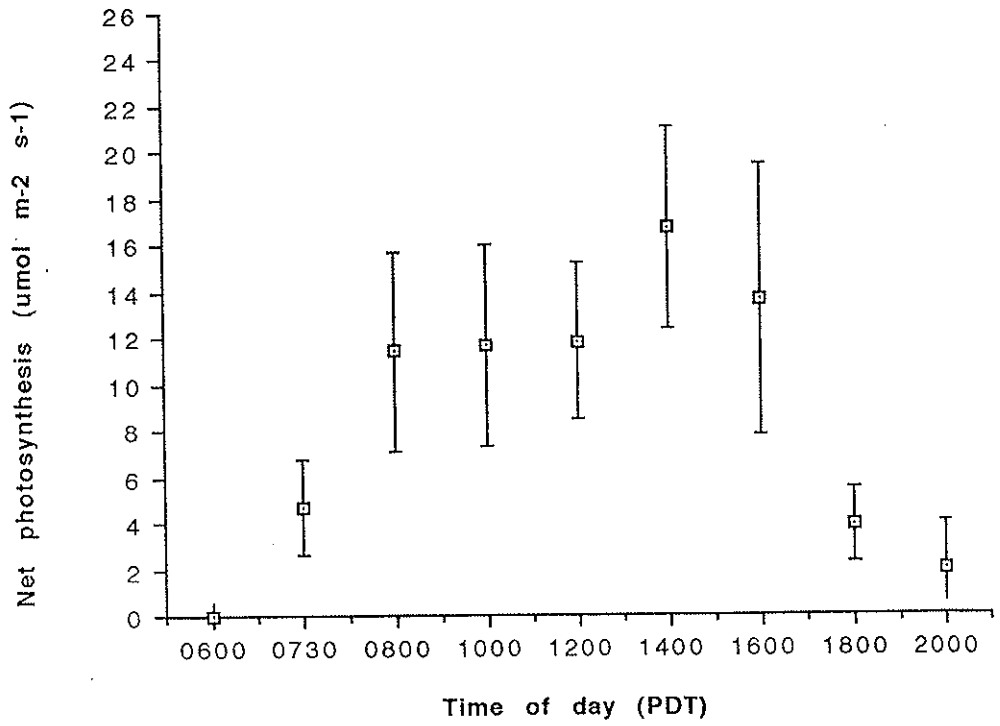

Fig. 36. Diurnal course of net photosynthesis for TS on August 4, 1995

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Nolte and Associates, Inc. 1996, Sacramento Regional Wastewater Treatment Plant Demonstration Wetlands Project, 1995 Annual Report.

Nolte and Associates, Inc. 1997, Sacramento Regional Wastewater Treatment Plant Demonstration Wetlands Project, 1996 Annual Report.

These reports can be obtained from Chuck Williams, Sacramento Regional Wastewater Treatment Plant, 8521 Laguna Station Rd. Elk Grove, CA 95758

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Perry, M., R. Post, C. Williams, G. Dombeck. 1998. Guidelines to vegetation design in constructed wetlands. Abstract submitted to Water Environment Federation Conference (WEFTEC), Orlando Florida, October 1998.

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Hojjati, M. 1995. Growth of aquatic macrophytes, *Scirpus acutus* and *Typha latifolia*, in the Demonstration Wetlands at the Sacramento regional Wastewater Treatment Plant. M. S. thesis, Graduate Group in Ecology, University of California, Davis, California.

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