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Two Landfill Cover Designs a Decade After Installation in a Semiarid Environment

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Two Landfill Cover Designs a Decade After Installation in a Semiarid Environment

ABSTRACT

Landfill covers should protect buried waste from water infiltration and biointrusion for periods ranging from 30 years to hundreds or even thousands of years. Despite this goal, most field studies of cover designs have been limited to just a few years, and have focused narrowly on water balances. An understanding of long-term cover performance will require an integrated approach that examines covers within the context of dynamic ecosystems. We evaluated characteristics of vegetation cover, rooting patterns, and soil profiles in landfill cover test plots that had been in place for over 11 years in a semiarid climate. The plots were of two designs; conventional plots consisting of 20 cm of topsoil over compacted, crushed tuff, and integrated plots consisting of 71 cm of topsoil over bio- and capillary-barrier layers of gravel, cobble, and crushed tuff. Evapotranspiration accounted for 94-97% of the precipitation input to the plots, seepage on all plots was less than 5% of the total precipitation input, and contrary to expectations, seepage on integrated plots exceeded that on control plots. After more than a decade, (1) the vegetation cover, biomass, and species diversity increased on all four plots, (2) integrated plots had more total biomass but less biomass from invading-species than the conventional plots, (3) rooting was more extensive in the integrated plots, but both designs limited the effective rooting depth to 70 cm, (4) little change had occurred in the soil profiles of either plot type or in the geotextile of the integrated plot type, and (5) infiltration occurred primarily via macropores, including root channels and animal burrows. Our results indicate that both cover designs were relatively effective during the first decade following installation, but ecological differences between the two designs after a decade are likely to become more important in determining cover effectiveness over longer time periods. Placing our work in the

why?

sounds like water balance

context of related studies, we suggest that ecological processes will become the dominant factor determining cover performance for periods of decades to centuries or longer.

INTRODUCTION

why isn't this "conventional" then?

Landfills with engineered liners and caps are widely used for the permanent disposal of hazardous and municipal solid waste. In order for these landfills to effectively isolate wastes and to minimize the risks of exposure to the public, the engineered barriers must exhibit long-term stability (Wing and Gee, 1994; EPA, 1989). Monitoring and maintenance of landfill sites will vary in duration, but are generally not expected to continue for more than 30 to 50 years after closure (Suter et al., 1993).

Although hazardous waste disposal sites are numerous in the semiarid to arid western U.S., relatively few studies have focused on landfill covers in semiarid or arid conditions. The U.S. Geological Survey has been evaluating hydrologic conditions at an arid waste burial site in the Mojave Desert since 1976 (Andraski et al., 1995). Anderson et al. (1993) examined the use of plants to extract soil moisture at arid waste burial sites. Waugh et al. (1994) determined the effect of plant species and various gravel-soil mixtures on waste site water balance at DOE's Hanford site. A number of other studies have focused on U.S. Department of Energy (DOE) sites (e.g. Waugh and Smith, 1996; Waugh et al., 1994; Nyhan et al., 1989a, b; Nyhan et al., 1990; Nyhan et al., 1997; Link et al., 1995; Lopez et al., 1988), and a lesser number on U.S. Department of Defense (DOD) sites (Paige et al., 1996; Warren et al., 1996; Hakonson et al., 1994). Because many DOE, DOD, and industrial waste disposal facilities are located in the western U.S., it is important to understand the unique parameters governing the long-term performance of landfill cover designs in semiarid environments.

With time, engineered landfill covers are subject to modification by natural environmental processes, particularly after postclosure care has ceased. Pedogenic processes can alter the structure, bulk density, and effective permeability of cover layers. Ecological changes can result in very different rooting patterns, potential evapotranspiration, and erosion potential. Climate changes may affect a site's water balance directly through increased or decreased precipitation and indirectly through influences on pedogenic and ecological factors. Numerous reports have pointed out the potential for landfill liners and covers to be modified by their natural environment (Waugh and Smith, 1996; Link et al., 1995; Gonzales et al., 1995; Nicholson and Safaya, 1993; Johnson and Urie, 1985). Several mechanisms whereby landfill barriers are likely to fail in the long term (>100 yr) are discussed by Suter et al. (1993), who recommend that perpetual care be required or that barriers be designed for long-term integrity.

Despite the clear importance of designing landfill covers that will perform adequately over long time periods, most field-based studies of landfill liners and caps provide just a few years of data. Modeling provides a means of projecting landfill performance further into the future, but the validity of such projections is limited by the quality and quantity of field data used for parameterization and testing of the models (Paige et al., 1996; Barnes and Rodgers, 1987; Nyhan, 1989). Fundamental ecological processes such as succession are not ~~even~~ factored into current models, yet they directly affect the integrity of landfill covers through biointrusion, erosion, and water balance. Waugh and Smith (1996) point out that natural analogs can sometimes be used to help project the effects of possible changes in climate, soil morphology, and ecology.

We evaluated the performance and the physical and ecological characteristics of two landfill covers more than a decade following installation in a semiarid environment—a control? conventional design with 20 cm of topsoil, and an test? improved design with 71 cm of topsoil over biointrusion and capillary barrier layers. Our objectives were to: (1) summarize the water budget

more objective up

relate ΔH_2O to 2,3,4,5,6 why?

over a decade; (2) determine how the vegetation community changed with time; (3) determine whether the two designs varied in total biomass after 10 years; (4) determine the root distribution within and among the plots; (5) examine the covers for changes in soil characteristics; (6) determine whether geotextile and polyethylene liners had deteriorated; and (7) examine infiltration patterns under ponded conditions. Our findings provide ~~important~~ information concerning the performance of both conventional and improved landfill covers over extended periods (i.e, more than a decade) following installation in a semiarid environment.

why? why? why? why?

METHODS

Two test plots for ~~each of~~ two landfill cover designs were installed during the spring and summer of 1984 at Los Alamos National Laboratory. The plots were intended to provide data for comparing water balance of two landfill cover designs in a semiarid environment. The two cover designs, designated "conventional" and "integrated", are shown schematically in Figure 1, and are described in detail by Nyhan et al. (1990). Briefly, the conventional plots consisted of 20 cm of sandy loam topsoil overlying 108 cm of compacted crushed tuff. The base of the plots included 5% slopes downward toward a perforated PVC drain pipe running the length of the plots. These drain pipes were connected to collection stations (one for each plot) for monitoring of seepage. The vertical walls of the plots were formed of corrugated sheet metal. The walls and base of the plots had a lining of 6-mil polyethylene. The conventional plots were 3.0 by 10.7 m in area. The integrated plots consisted of 71 cm sandy loam topsoil, 46 cm of 5- to 10-cm-diameter gravel, 91 cm of 10- to 30-cm-diameter cobble, and 38 cm of crushed tuff. The walls and floor of these plots were constructed in the same way as were the conventional plots, with the exception of an overhanging shoulder with a perforated drain pipe for collecting interflow from the topsoil layer (see Figure 1). The topsoil and gravel layers were separated by a high conductivity geotextile

"narrowly focused"

(600X Brand, manufactured by MIRAFI, El Toro, CA) to maintain the sharp interface between these different textured layers. This boundary was constructed with a 5% slope toward the shoulder interflow drain. The integrated plots were 3.7 m by 10.7 m at the surface, the greater width due to the overhanging shoulder in the topsoil and gravel layers.

Data for estimating water balance on each plot were collected continually from August 13, 1984 to November 21, 1994. All four plots included vertical aluminum access tubes for monitoring soil moisture content using a neutron probe moisture gauge. Details of soil moisture measurement procedures and calculations of soil water storage, as well as methods for seepage (leachate), interflow, and precipitation measurements are provided in Nyhan et al. (1990).

The plots were initially seeded with blue grama (*Bouteloua gracilis*) and western wheatgrass (*Agropyron smithii*) in the spring of 1984. Vegetation establishment was aided by application of supplemental water during the summer months of that year. Subsequently the plots received only natural precipitation throughout the 10-year study period. Estimates of biomass for 1986 are reported in Nyhan et al. (1990). The vegetation was resurveyed in the spring of 1995. Above-ground vegetation was measured using transects (n = 12 3-m wide rows with measurments every 6 cm along each row) and quadrats (20 cm x 50 cm) to determine biomass in terms of ground cover and foliar cover for each species present. Quadrats were located around the periphery of the plots (EDGE, n = 6 / plot), around neutron probe access tubes (TUBE, n = 6 / plot), and in the centers of the plots (CENTER, n = 8 / plot). All vegetation within the quadrats was clipped at ground level, bagged, dried and weighed. Leaf area index (LAI) was also determined for the green leaf component (spereated from standing dead biomass) runing each sample through a LICOR leaf area meter twice and averaging the results. Leaf area and biomass were then correlated for all of the plots.

where is this in your objectives?

After the vegetation survey was complete, ponded infiltration tests were conducted in August 1995 to compare cover designs and evaluate the role of macropores. On each plot, a 0.9-m-by-1.9-m sheet-metal border was pressed 5 cm into the topsoil. A solution of red fluorescein dye in water was ponded to a depth of 25 cm inside each border. The depth of the solution was recorded at regular time intervals until infiltration was complete.

After vegetation surveys and infiltration testing were completed, all four plots were excavated from the side to obtain pedologic descriptions, sampling, and root counts. Roots were counted on 50-cm-long transects on vertical and horizontal surfaces at 10-cm depth intervals, from 5 to 105 cm in the conventional plots and from 5 to 75 cm in the modified plots. Vertical- and horizontal-surface counts were obtained at the same depths and locations. All fine (<2 mm diameter) and medium (2-5 mm diameter) roots intersecting the 50-cm-long transects were counted.

Bulk density cores were collected at plot walls and plot interiors, at depths of 5, 10, 20, 30, 55, and 100 cm. Cores were obtained using 6.3-cm diameter by 7.5-cm-long brass tubes. The cores were oven dried for 48 hours and weighed. Bulk density was calculated by dividing the oven-dry sample weight by the known volume of the cores. These data were analyzed using a one-way analysis of variance (ANOVA) with P = 0.05 significance level.

RESULTS

Water balance

Water balance data collected and totaled over ten years (Table 1) show that on the control plots ~96% of total moisture input was lost through evapotranspiration, whereas on the integrated plots ~94% was lost a through evapotranspiration. Seepage production was quite low on all four plots. The two conventional plots produced seepage totaling about 3% of total precipitation

inputs, while, contrary to expectations, the integrated plots more slightly more seepage (~4%). The lower evapotranspiration in the integrated plots was reflected in greater storage of moisture within the thicker topsoil layers, and in small amounts of lateral drainage (interflow) from that layer (less than 1% from both plots).

Soil development

We found that little or no discernible soil development had taken place since installation of the plots. There was no horizonation other than that established for each design. Macropores were present, but there was no corresponding clearly defined soil structure. Bulk density was variable both within and among plots, but did not show any patterns consistent with normal pedogenesis. Bulk densities ranged from 1.17 to 1.45 Mg m^{-3}, with an overall mean of 1.34 Mg m^{-3} (n=28). There were no significant differences in bulk density with respect to sampling depth or plot type (Table 2).

integrated

The geotextile separating the topsoil from the bio/capillary barrier in the improved plots was found to be essentially intact. While large numbers of fine roots had penetrated the textile, the material itself did not appear to have lost integrity, i.e. there were no holes or tears. Moreover, the geotextile maintained the cover integrity in that no topsoil had passed through the textile into the gravel/cobble layer below. The gravel/cobble layer itself contained a minor component, estimated at less than 5% by volume, of finer soil particles, primarily sand sized grains. It is probable that this sand was present in the gravel and cobble fill at the time of installation of the plots.

Vegetation

Vegetation characteristics varied by plot type both early in the project and at its conclusion, as shown in Figure 2. Initially in 1986, there was more establishment of the seeded grasses on the integrated plots than on the conventional plots. Total biomass increased between 1986 and 1995, with the exception of integrated plot I1. In 1986, the deeper topsoil of the integrated plots supported much more biomass than did the shallow topsoil of the conventional plots. However, this pattern did not hold true in 1995: integrated plot I1 had less biomass than control plot C1 in 1995.

Species composition differed between the two plot designs. The integrated plots saw both real and proportional declines in blue grama biomass from 1986 to 1995. In 1986, the integrated plots had a much greater proportion of blue grama, whereas the conventional plots had a greater proportion of western wheatgrass (Figure 3). Other invading species also became established by 1995. These invading species accounted for about one third of the biomass on each of the conventional plots, but were only a minor component of the integrated plot biomass (Figure 3).

Rooting

Roots were found in almost all portions of the covers, their abundance decreasing with depth (Figure 4). A few fine and medium roots were observed in the gravel layers of the integrated plots, although the root-count transects in those layers did not register any. In the case of the modified plots, abundant fine roots were also concentrated along the geotextile separating the topsoil from the gravel layer. These roots had not penetrated the geotextile, instead forming a continuous root mat on the base of the topsoil. Only one instance was seen of a larger root (2-3 mm dia.) penetrating the geotextile, and that root did extend into the gravel layer. The geotextile

barrier defined the practical limit of rooting for the herbaceous species on these plots, suggesting that the depth of infiltration was also largely coincident with this barrier.

Ponded infiltration

The ponded infiltration tests showed that the plots exhibited a linear infiltration function, with the exception of conventional plot 1 (Figure 5). This plot contained extensive pocket gopher burrows, which were observed during excavation of the plot (Figure 6). This resulted in infiltration that was very rapid but decreased exponentially with time. The highest infiltration rates, aside from the gopher-modified conventional plot C1, were in integrated plots I1 and I3 (3.5×10^{-3} and 3.0×10^{-3} cm/s, respectively). Conventional plot C2 had an infiltration rate of 2.3×10^{-3} cm/s.

Excavation showed that much of the infiltration occurred via macropores in both the topsoil and crushed tuff layers. In the topsoil of both designs there was significant staining of the soil matrix as well as root channels and other macropores. Matrix staining decreased significantly within 5 to 10 cm of the soil surface, while macropore staining extended through the entire thickness of the topsoil. In the crushed tuff (conventional plots only) staining occurred in and surrounding root channels and animal (pocket gopher and ant) burrows, with essentially no staining of the matrix (Figure 7). In the integrated plots there was no staining in the gravel or cobble layers except in a few locations next to the plot walls and neutron probe access tubes. In these cases it was clear that seepage had proceeded preferentially down the plot walls and access tubes.

implications for interpret of neutron probe meas.

DISCUSSION

Our water balance data show that both cover designs were effective at controlling seepage. Seepage was less than 5% of the total precipitation input for all plots. Contrary to expected, the conventional plots yielded slightly less seepage than the integrated plots. Recent research on capillary barriers similar to the integrated plots of this study indicate that slopes of > 5% are required for effective generation of interflow and associated reductions in seepage (Nyhan et al. 1997). The reduced evapotranspiration for the integrated plots can be attributed primarily to the greater storage capacity of the thicker topsoil layer of the integrated design. The interflow drains in the integrated plots also diverted a small amount of potential seepage. Evapotranspiration clearly is extremely important to cover performance in this semiarid climate, accounting for about 94-96% of the water balance.

is this also true for "natural" interflow?

Soil development was not significant 11 years after plot installation. This was not a surprising result given that soil-forming processes are slow, particularly in semiarid and arid climates. It does add support, however, to the idea that even complex cover designs may be sustainable at least over the 30-year post-closure monitoring/maintenance period prescribed by RCRA (EPA, 1989). The lifespan of the geotextile, used in this case to maintain the boundary between topsoil and capillary barrier layers, is not known. It is expected, however, that this material will break down significantly within a few decades, allowing translocation of topsoil into the gravel and cobble layers. Penetration of the geotextile by roots of trees and shrubs will probably accelerate its breakdown. On the time scales of hundreds or even thousands of years during which hazardous waste could pose a public health risk, soil development will become more of a factor influencing erosion and water infiltration through covers.

more soil, less infiltrat erosional vs. soil pedogenesis

Vegetation dynamics differed between the two plot types. Biomass increased significantly after initial establishment, as expected. The thicker topsoil of the integrated plots appears to have

allowed for better early establishment of the two original (seeded) species, blue grama (*Bouteloua gracilis*) and western wheatgrass *(Agropyron smithii*). Species composition also was influenced by landfill cover design. In 1986, blue grama dominated the integrated plots, while western wheatgrass made up half or more of the biomass on the conventional plots. In 1995, the species composition of all plots had changed significantly, with other invading species accounting for about one-third of conventional plot biomass, and a small but significant proportion (7-13%) of integrated plot biomass. After 11 years from initial establishment, the two designs still had substantially different plant covers, suggesting that these designs are progressing down distinct successional pathways. The conventional design is clearly more susceptible to establishment of invading species than is the integrated design. It is not clear what the plant cover of either design may be like after 30, 100, or 500 years, but these data suggest that cover design has a significant impact on plant succession.

The invading species on both plot types were limited to herbaceous plants. However, woody are expected to establish on both plot types after some time period (Tierney and Foxx, 1982). At another site within Los Alamos National Laboratory, a landfill that had been covered with about 90cm of topsoil (similar to the conventional plots in this study) and had been closed for 34 years was found to have a number of tree and shrub species growing on the cover, with some trees rooting directly into waste material (Wenzel et al., 1987). Pocket gophers had also exposed waste material. While that landfill (closed in 1948) did not include the liner and cover technology required today, its condition shows that a variety of woody, deep-rooted species can be expected to appear on landfill covers within 30 years. The cover design chosen may influence the extent to which trees and shrubs are able to establish, and how deeply their roots may extend below the surface.

Same ecotone?

While tree and shrub roots may pose a threat to the integrity of landfill covers, many woody evergreen species also are able to remove soil moisture throughout the year. Many of the landfill sites at Los Alamos are situated within piñon-juniper (*Pinus edulis-Juniperus monosperma*) woodlands, and both piñon and juniper transpire throughout the winter (Breshears, 1993). A significant proportion of the annual precipitation at Los Alamos occurs during the winter, and fluctuating temperatures can result in snowmelt-saturated soils. The dormant grassy species cannot remove this excess moisture, but piñon and juniper, which use moisture even during the winter months, can help dry the topsoil and prevent saturated conditions that could lead to seepage through the cover. Thus these woody species can help minimize seepage through buried waste.

It is important to recognize the ability of burrowing animals to negate the effectiveness of landfill covers. In our case, a single pocket gopher burrow increased the infiltration capacity of a cover by nearly an order of magnitude, and moved ponded water (analogous to an intense thunderstorm or rapid snowmelt) rapidly below the installed cover. Therefore biobarriers, such as our gravel and cobble layers or gravel incorporated into the topsoil, may be essential to even the short-term success of any cover design.

The data from this study, in conjunction with others, have helped us form a conceptual picture of the long-term performance of landfill covers in semiarid regions. The performance of a landfill cover is dependent on both the engineering factors that form the basis of the initial cover and the ecological factors that affect the cover through time (Figure 8). With time, we expect the relative importance of ecological factors in cover performance to increase, while the relative importance of engineering factors should decrease, as discussed by Suter et al. (1993). The exact shape of the curves will ~~of course~~ depend on the cover design and local climate. For a conventional design at Los Alamos, we can estimate some time points along the curve. Our study

LANL ?

and that of Nyhan et al. (1990) show that the conventional design remained intact for over a decade, while the study of Wenzel et al. (1987) on a similar cover design at Los Alamos shows breakdown of the cover and dominance of ecological processes in less than 35 years. Our study and that of Nyhan et al. (1990) also show that the integrated plots remained intact for over a decade. Longer term studies of improved landfill covers, such as the integrated cover that we studied, are needed to determine performance for periods of 30 years or longer. Important insights into water balance can be obtained by studying "natural systems" that are long-term analogs of landfill covers. Related studies of water balance in piñon-juniper woodlands at Los Alamos are providing such insights (Wilcox, 1994; Breshears et al., 1997a, 1997b; 1998; Davenport et al., 1998). The results that we report here provide an important step in extending the evaluation of landfill covers from the first initial years to periods of decades or longer over which landfill covers must perform to minimize risks to human health and the environment.

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Table 1. Water balance for conventional (C) and integrated (I) plots, August 1984 to November 1994 (percentages of total precipitation inputs).

PLOT	Precipitation (cm)	Evapotranspiration (%)	Storage† (%)	Interflow§ (%)	Runoff* (%)	Seepage (%)
C 1	496	95.7	1.1	NA	0	3.2
C 2	496	96.7	0.4	NA	0	2.9
I 1	496	93.7	1.9	0.0	0	4.3
I 2	496	93.7	1.3	0.7	0	4.3

* Runoff was eliminated by zero surface slope and metal flashing around plot borders to contain surface water.

† Storage estimated from neutron probe soil moisture data (Nyhan et al., 1990).

§ Interflow from side shoulder drains in integrated plots only.

¶ Evapotranspiration calculated by difference.

Table 2. Soil characteristics from vertical profiles of conventional (C) and integrated (I) plots.

Plot	Depth (cm)	Texture *	Structure†	Bulk density, wall (Mg/m^3)	Bulk density, interior (Mg/m^3)
C1	5	grSL	SG	-	-
	10	grSL	SG	1.17	1.43
	20	grSL	SG	1.20	1.43
	30	LS	M	1.17	1.33
	55	LS	M	-	-
	100	LS	M	1.22	1.35
C2	5	grSL	SG	-	-
	10	grSL	SG	1.43	1.33
	20	grSL	SG	1.44	1.30
	30	LS	M	1.29	1.33
	55	LS	M	-	-
	100	LS	M	1.30	1.38
I1	5	grSL	SG	1.32	1.38
	10	grSL	SG	-	-
	20	grSL	SG	-	-
	30	grSL	SG	1.35	1.21
	55	grSL	SG	1.38	1.45
	100	gravel	SG	-	-
I2	5	grSL	SG	1.41	1.33
	10	grSL	SG	-	-
	20	grSL	SG	-	-
	30	grSL	SG	1.34	1.35
	55	grSL	SG	1.40	1.40
	100	gravel	SG	-	-

* grSL = gravelly sandy loam; LS = loamy sand

† SG = single-grain; M = massive

List of Figures

Figure 1. Cross-sections showing design of cover plots.

Figure 2. Total biomass (g/m^2) for conventional and integrated plots in 1986 and in 1995.

Figure 3. Blue grama, western wheatgrass, and other species as percentages of total biomass on conventional (C) and integrated (I) plots in 1986 (Nyhan et al., 1990) and 1995.

Figure 4. Root abundance with depth in conventional and integrated plots.

Figure 5. Ponded infiltration curves for conventional (C) and integrated (I) plots. Best fit curves are linear for plots C2, I1, and I2, exponential for plot C1 (due to gopher burrows). C1: y = 144.66 * e^(-0.10192x), R= 0.90048; C2: y = 286.95 - 1.4393x, R= 0.99349; I1: y = 314.45 - 2.134x, R = 0.99384, I2: y = 238.45 - 1.8026x, R= 0.99766.

Figure 6. Plot C1 showing the effects of pocket gophers.

Figure 7. Plot C2 showing dye-stained root channels in crushed tuff.

Figure 8. Conceptual graph illustrating likely trends in the relative influence of engineering and environmental factors in the long-term effectiveness of engineered landfill covers. A: Three years or less after installation (Nyhan et al., 1990). B: Ten years after installation (this paper). C: Thirty years after closure (Wenzel et al., 1987). D: One century or more after closure (no studies available).

Fig. 1.

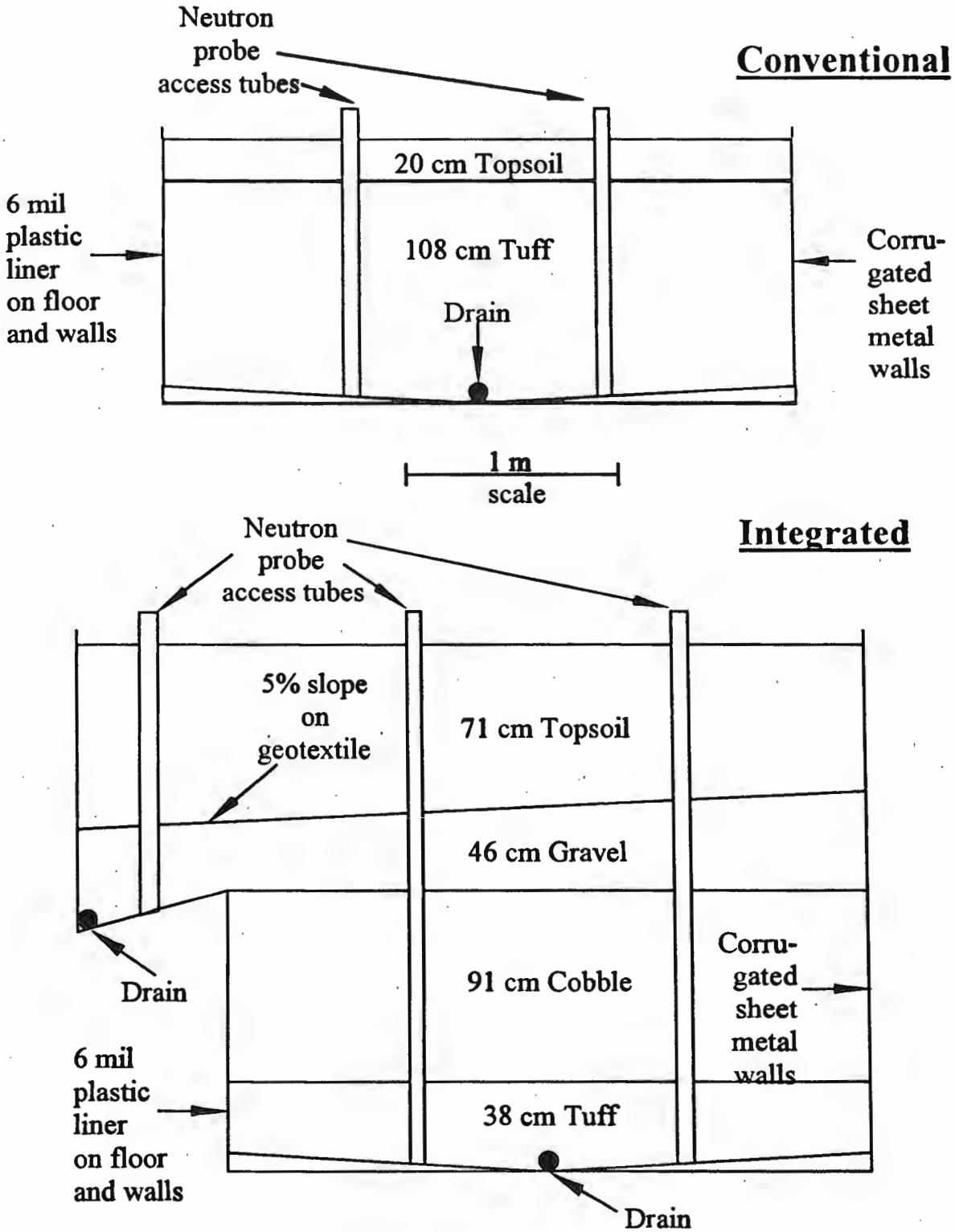

Conventional
Neutron probe access tubes
20 cm Topsoil
108 cm Tuff
Drain
6 mil plastic liner on floor and walls
Corru-gated sheet metal walls
1 m scale
Integrated
Neutron probe access tubes
5% slope on geotextile
71 cm Topsoil
46 cm Gravel
91 cm Cobble
38 cm Tuff
Drain
Drain
6 mil plastic liner on floor and walls
Corru-gated sheet metal walls

Fig. 2.

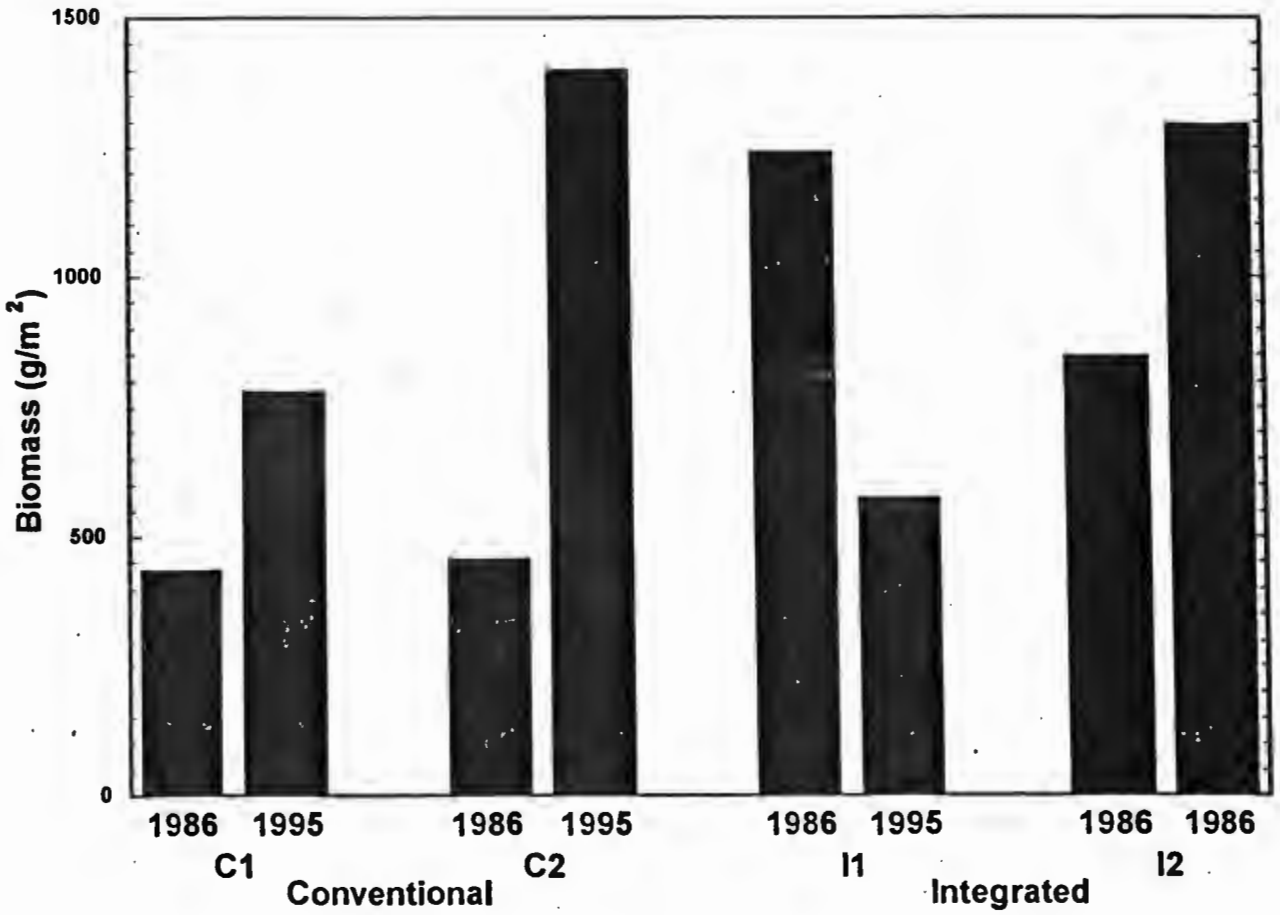

1500
1000
500
0
Biomass (g/m 2)
1986
1995
1986
1995
1986
1995
1986
1986
C1
C2
I1
I2
Conventional
Integrated

Fig. 3.

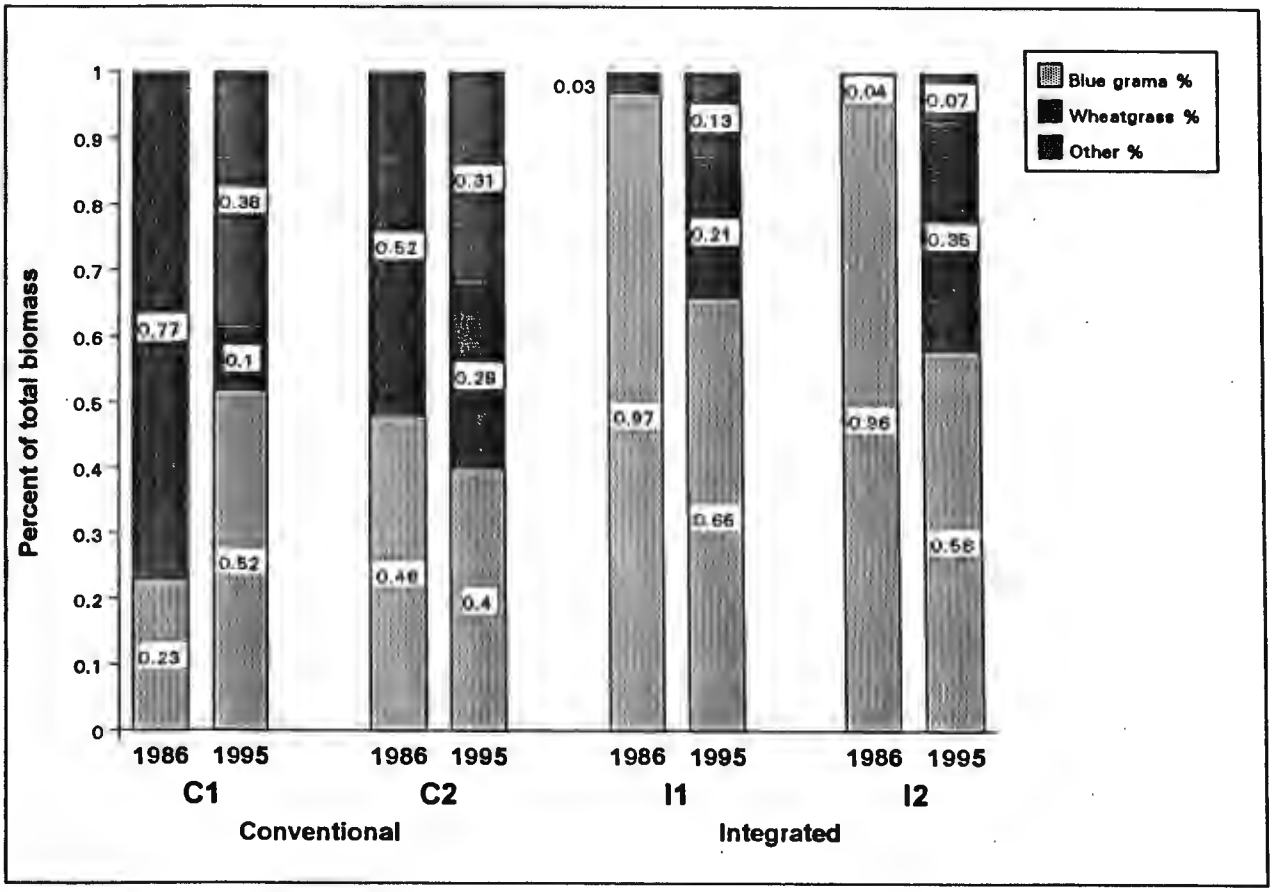

Percent of total biomass
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.77
0.23
0.38
0.1
0.52
0.52
0.46
0.31
0.28
0.4
0.03
0.97
0.13
0.21
0.66
0.04
0.96
0.07
0.35
0.58
1986
1995
1986
1995
1986
1995
1986
1995
C1
C2
I1
I2
Conventional
Integrated
Blue grama %
Wheatgrass %
Other %

Fig. 4.

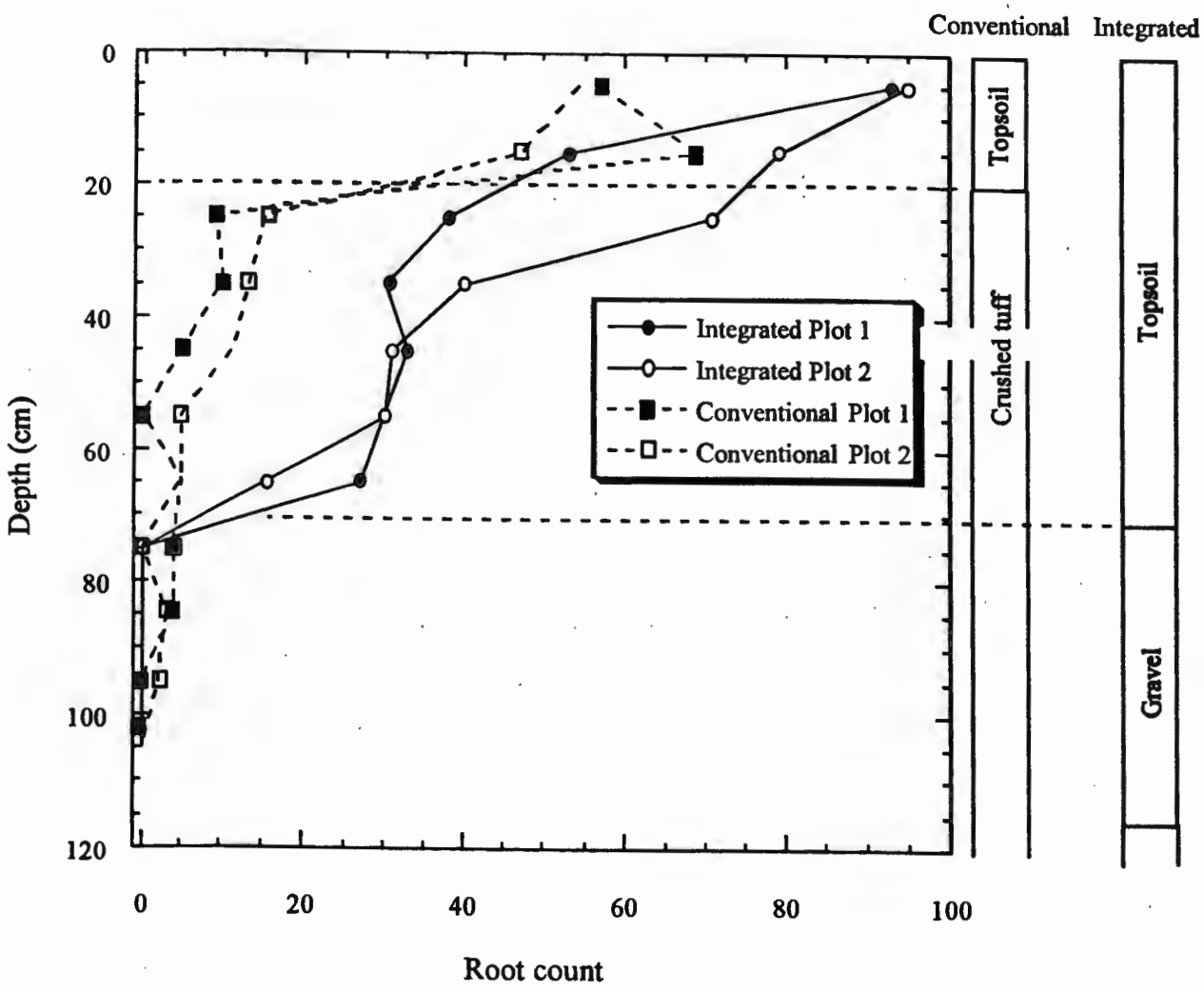

Conventional
Integrated
Topsoil
Crushed tuff
Topsoil
Gravel
Integrated Plot 1
Integrated Plot 2
Conventional Plot 1
Conventional Plot 2
Depth (cm)
0
20
40
60
80
100
120
0
20
40
60
80
100
Root count

Fig. 5.

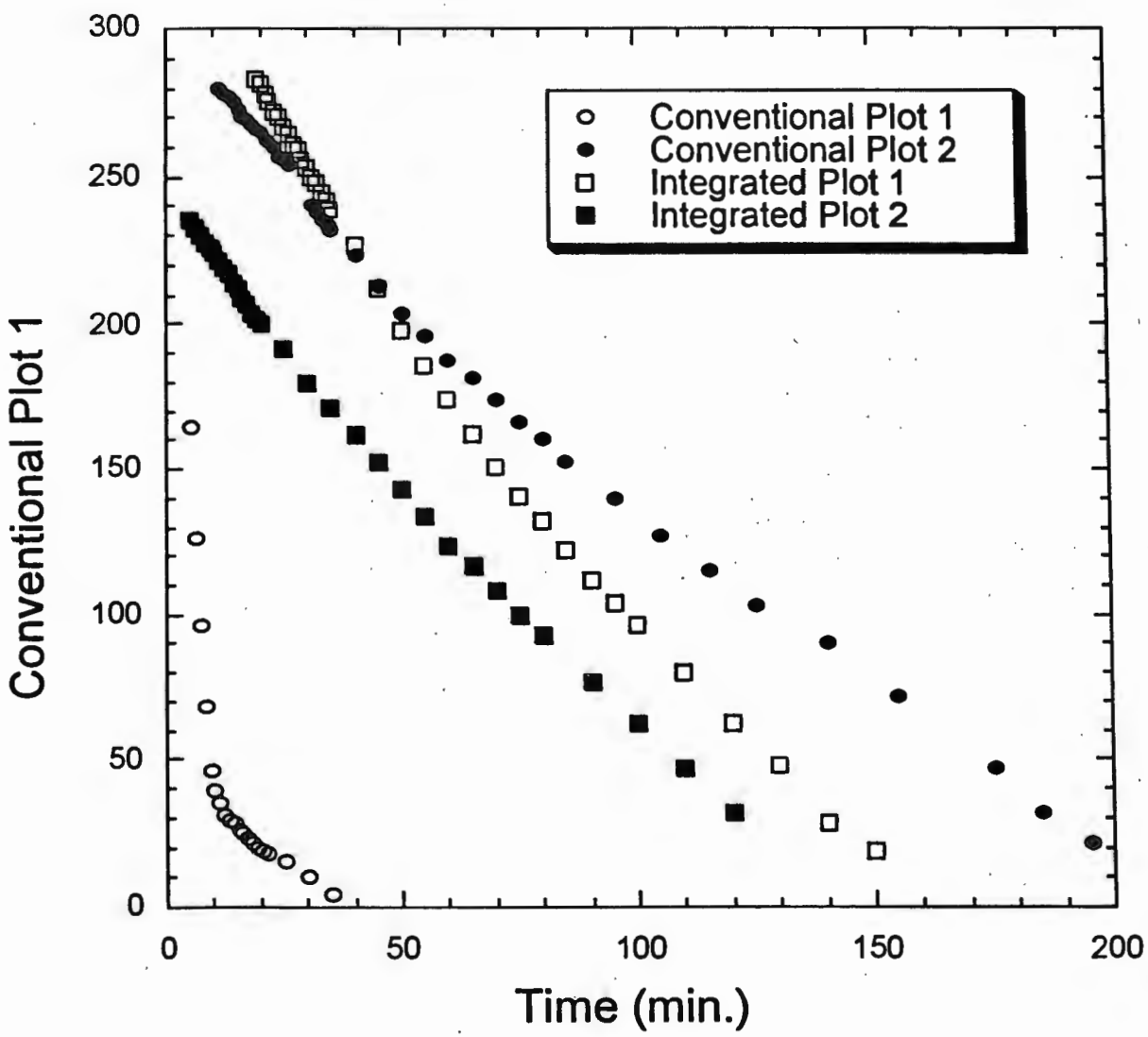

Conventional Plot 1
Conventional Plot 2
Integrated Plot 1
Integrated Plot 2
Conventional Plot 1
Time (min.)
0
50
100
150
200
250
300
0
50
100
150
200

Fig. 6.

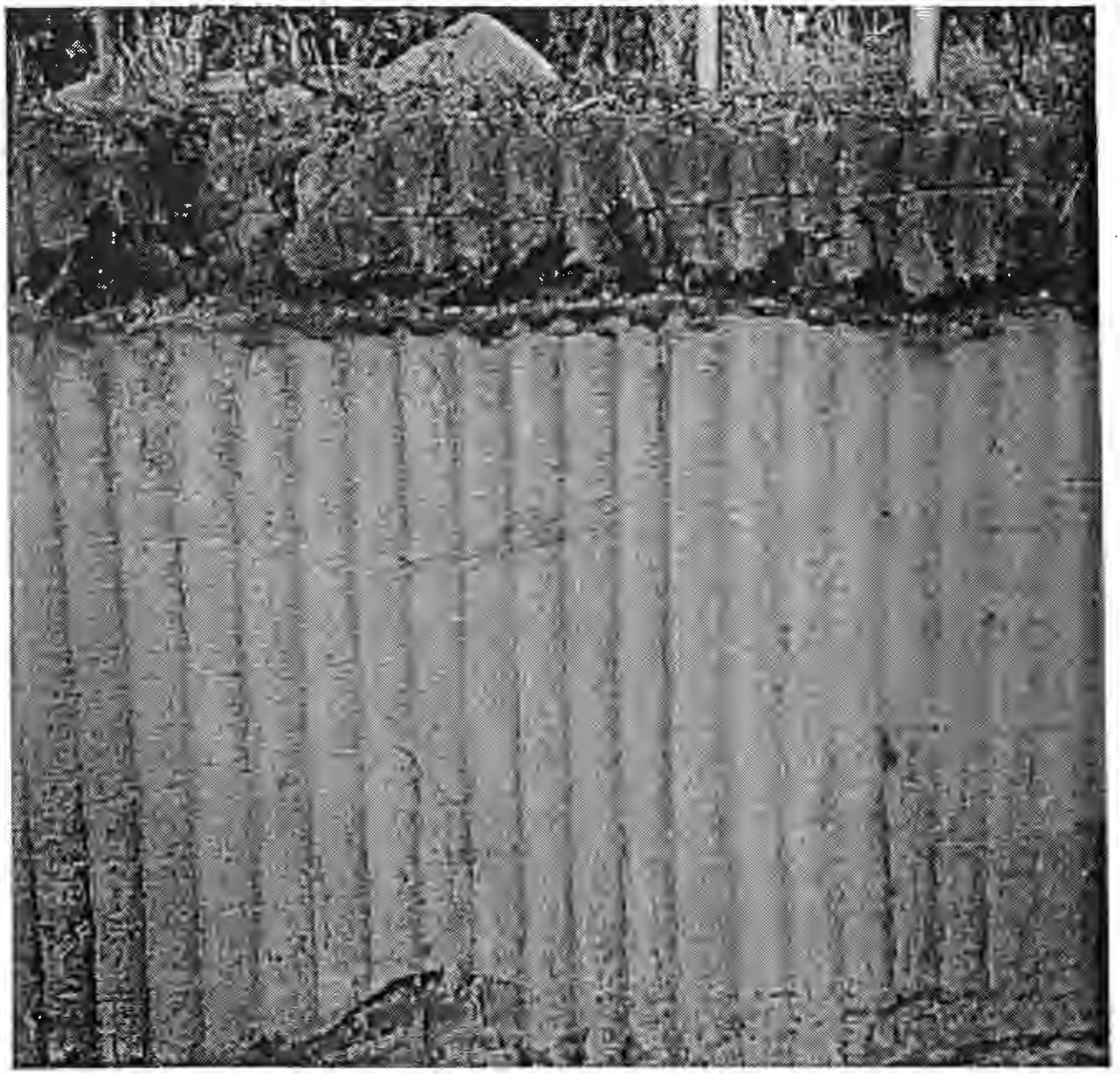


Fig. 7.

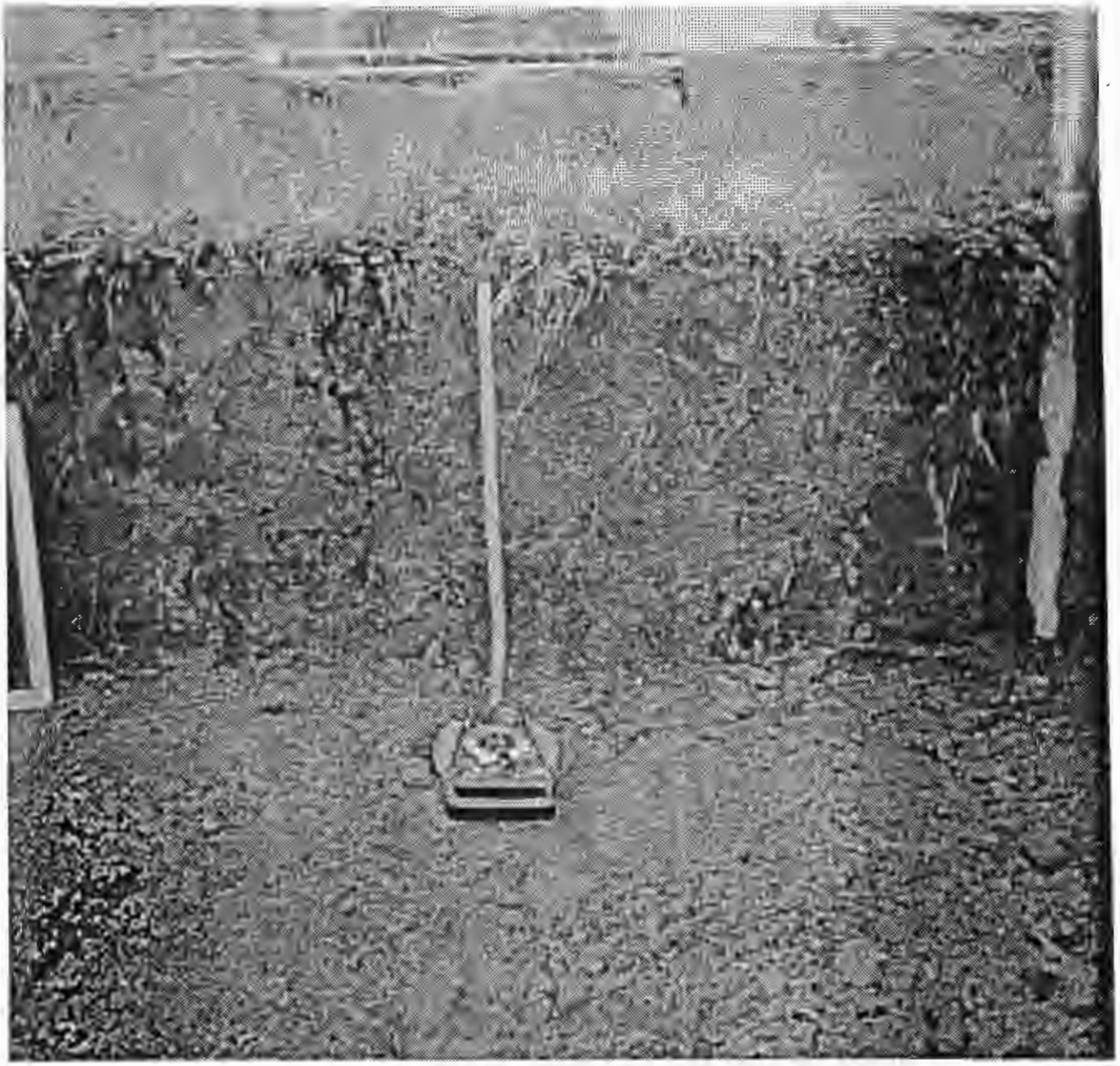
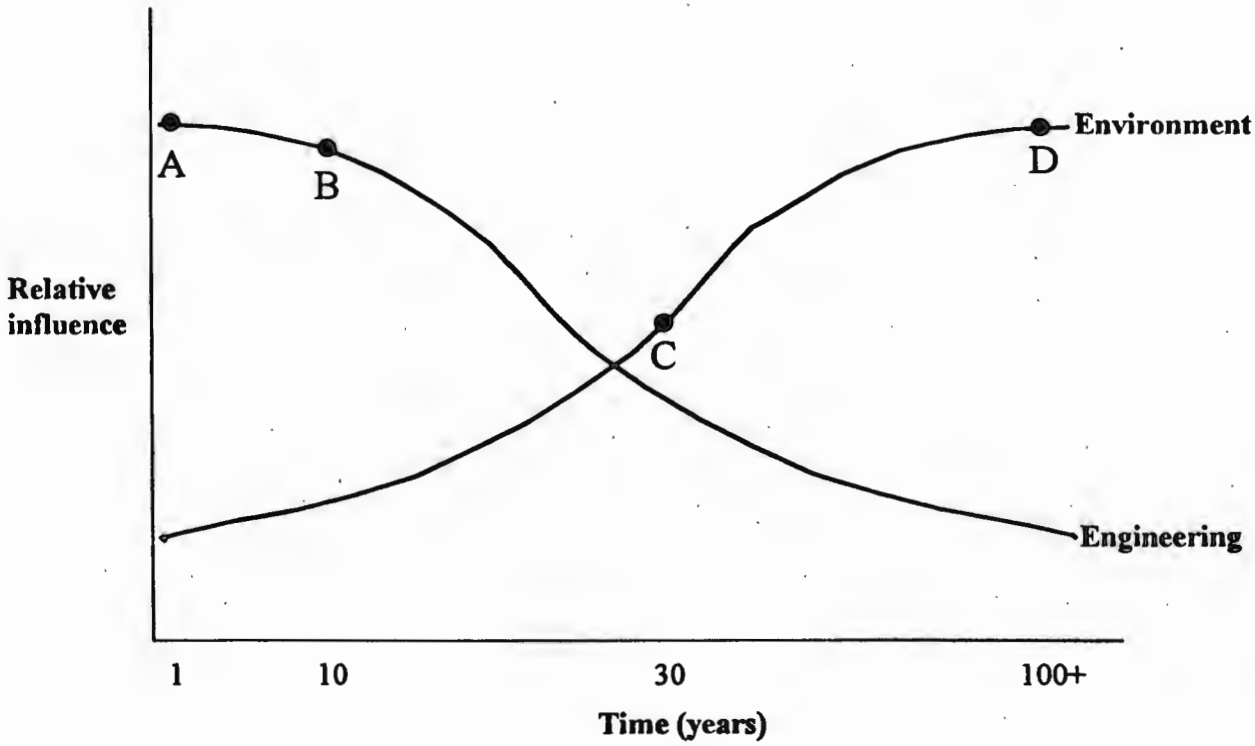


Fig. 8.


Environment
A
B
D
Relative influence
C
Engineering
1
10
30
100+
Time (years)