Paper 2 (draft)

Effects of skidding on soil infiltration in west central Alberta

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Abstract

Soil compaction during forest harvesting generally reduces macropore space, which reduces infiltration of water and increases the potential for surface erosion. Effects of 3, 7 and 12 skidding cycles on tension infiltration of surface soil and their persistence for three years were evaluated at 14 sites representing a range of soil texture and compaction in foothill and boreal forests of Alberta. Significant compaction, based on a significant ($p<0.05$) increase in bulk density, resulted in a significant decrease in infiltration rate after the first 3 skidding cycles at 8 sites; the decrease in infiltration at the other sites was not significant. The soil wetness at the time of skidding was the dominant factor determining whether a compaction caused a significant decrease in infiltration. Significant compaction by mostly wide-rubber tired skidders and forwarders reduced infiltration when soils were wetter than –15 kPa. An additional traffic to 12 cycles did not cause a further significant decrease in infiltration during skidding although the recovery rate was slower in more trafficked soil. In two years after skidding, infiltration recovered somewhat due to frost action in surface layer but the recovery to control level occurred on only the 3-cycle treatment.

The heavy machinery used to skid logs compacts forest soils (Froehlich and McNabb 1984). Compaction-induced alteration of pore space affects soil water transmission (Warkentin 1971). Significant reduction in soil hydraulic conductivity following mechanized clearcut forest harvesting was reported in different parts of the world (Greacen and Sands 1980, Gent et al. 1983, 1984, Wronski 1984, Jackobson and Greacen 1985, Incerti et al. 1987, Aust et al. 1992a, Rab 1994, Alban et al. 1994, Huang et al. 1996). However, a further generalization on the effects of different types of equipment, levels of skidder traffic, and persistence of the effects in time are difficult to make on the basis of these data. Answering these questions has a potential for important management implications because a minor change in infiltration rate of surface soil may alter the root environment, increase the potential for water erosion or cause water-logging at the scale of a planting microsite, cut-block or watershed. Objective of this study is to determine the effects and post-effects of skidder traffic of different intensity on the infiltration rate of surface soil in foothill and boreal Alberta forests.

Materials and methods

A total of 14 sites were selected in mature conifer stands across west-central Alberta where a substantial amounts of forest operations occur in summer. Most sites are located in the Southern Alberta Uplands ecodistricts of the Lower and Upper Boreal Cordilleran ecoregions (Strong 1992). The Lower ecoregion is dominated by lodgepole pine or white spruce with some aspen on well-drained soils while the Upper ecoregion is dominated by lodgepole pine with a small component of white or black spruce depending on the soil wetness (Corns and Annas 1986).

The sites were skidded as part of normal harvesting operations. At every site, four identical blocks were established in felled timber prior to skidding. Each block contained four levels of skidding activity: a control with 0 skidding cycles, 3, 7, and 12 skidding cycles. A skidding cycle is one empty and one loaded pass of a skidder over a corridor approximately 6 m wide and 40 m long. A control area, 10 m wide, separates each level of skidding activity.

Immediately after skidding, four sampling points were randomly selected within each treatment. Bulk density was measured in soil cores, 3 cm in height and 7.6 cm in diameter collected at the midpoint of the 5, 10, and 20 cm depths in each point of all four treatment blocks at each site (McNabb and Startsev 19...). One, the most representative block, was selected at each site for infiltration rate measurements. The infiltration rate was measured at the top of the mineral soil in four random points of every treatment using tension infiltrometers (Perroux and White 1988). The tension infiltrometers have become a common tool for *in situ* estimation of hydraulic properties in both forest and agricultural soils (Clothier and White 1981, Wilson and Luxmoore 1986, 1988, White and Perroux 1989, Ankeny et al. 1990, Reynolds and Elrick 1991). Prior to measurements, the forest floor and slash were carefully removed to minimize disturbance to the mineral soil. A circle of 105 microns mesh polyester cloth (precut to the outer diameter of the device base) was laid on the infiltration surface. Fine sand was placed on top of cloth, leveled and smoothed. The water potential of -1.5 cm of water was set on device that allowed near saturated water flow excluding only pores larger than 2000 μm.

Analysis of pore size distribution indicated that pores of this size are rare in the study soils (unpublished data). The relatively high soil water contents prevented measurements at lower water potentials. Therefore, only unconfined infiltration rate at near saturation could be estimated. The base of infiltrometer was placed onto the contact material, using a slight twist to ensure contact. Water flow into the soil was measured by monitoring the rate of fall of the water level in the reservoir using the reservoir scale and stopwatch. Steady state flow was assumed when the rate of fall becomes constant that was usually attained within 30-45 min.

The measurements of infiltration rate were repeated in one, two and three years following skidding in the points within 0.5 m of each of the previous location. The year when sites were skidded and infiltration rate measured first time, and the three consequent years, when infiltration rate was remeasured, will be further referred to as years 0, 1, 2, and 3, respectively.

Data distribution was tested for normality with *w*-statistic (Shapiro and Wilk 1965); transformations were used as necessary. The data analysis was performed using SAS 6.11 mixed procedure with time as repeated factor (Littell et al. 1996) followed by estimation of differences among least square means.

Results

Most sites were skidded with rubber-tired grapple skidders (John Deer 648E, 748E or Timberjack 480B, 450C), but two sites were skidded with 3-axle forwarders (Valmet 540 and Timberjack 520A) and one site - with a tracked crawler (CAT D4H

TSK) (Table 1). Most grapple skidders were equipped with tires 1.1 m wide, at least on the rear axle.

Soils were predominantly Gray Luvisols that vary in degree of gleying and depth to mottles. Brunisols were found at only two southern sites. Soils were relatively uniform in texture due to soil formation on similar parent materials - tills (Strong 1992).

Soil wetness, as indicated by soil water potential, varied widely across the sites at the time of skidding (Table 1). Soil wetness determined whether bulk density increased significantly during skidding. The values of bulk density are for cores collected from all four replications of the control. A significant increase in bulk density occurred after 3 skidding cycles at eight sites where water potential was higher than about -15 kPa. The six sites, where the soil was at water potential less than -15 kPa, were not significantly compacted after 12 skidding cycles. No obvious differences in the effects of skidding on infiltration rate were found among the types of equipment and types of soil.

The four-year infiltration data is not complete at the sites 10 through 14 because of one-year delay in installation of treatments. Besides, the infiltration could not be remeasured at several sites due to poor weather conditions that complicated access to the sites and because of high groundwater tables or partial flooding in the measurement locations. This was one of the reasons to use the SAS mixed procedure, which is capable of handling missing data in the repeated measure analyses (Littell et al. 1996). The missing data is indicated by blanks in Table 2 that contains geometric means calculated by year, site and treatment. Arithmetic means and standard errors are not valid on this data set because the data distribution is skewed to the left and, obviously, is representative of a lognormal distribution (Fig 1). The natural logarithm transformation eliminated the asymmetry and the distribution passed Shapiro-Wilk test for normality at 0.05 probability level that validated parametric statistics on the $\log_e$-transformed data set (Tabachnick and Fidell 1989).

Analysis, performed on the entire data set, indicated a significant treatment effect that did not change over time (Table 3). The main effect of time was not significant. The site effect could not be estimated as classification factor in the model because of non-replicated design with respect to site. Because the sites primarily differed by whether the soil was significantly compacted, the eight sites with significantly compacted soil were analyzed separately from the other sites. The analysis showed that infiltration rate was significantly affected by the number of skidding cycles only at the sites, where the increase in soil bulk density following skidding was significant.

Analysis of differences among least square means indicates that the first three skidding cycles reduced the infiltration rate by about a half (Fig. 2). Additional trafficking of soil to 12 skidding cycles did not result in a further significant decrease in infiltration rate. Although interaction between treatment and time is not significant, the data indicate a recovery of infiltration in 3-cycle treatment in two years after skidding. The heavier trafficked treatments remain significantly different from control in 3 years after skidding.

Discussion

The decrease in infiltration following skidding was only significant if a significant increase in bulk density occurred. At the sites that were skidded at soil water potentials lower than about -15 kPa, neither bulk density nor infiltration rate changed significantly

(Tables 1 and 3). This is additional evidence that trafficking of soil at water contents below field capacity by skidders, equipped with wide tires, causes no significant modification to the soil pore space. No obvious changes occur not only in the total pore volume but also in other characteristics of pore geometry affecting hydraulic conductivity, such as pore continuity and tortuosity. At compacted sites, a significant change in both the bulk density and infiltration occurred following the first three cycles with little changes caused by additional traffic (Fig. 2). The decrease in infiltration that occurs simultaneously with an increase in bulk density during soil compaction seems logical. Freitag (1971) considered the decrease in infiltration rate as much a measure of compaction as the increase in bulk density. When the increase in bulk density is not associated with a significant decrease in infiltration as in Aust et al. (1992b), the presence of a large percent of discontinuous, hydrologically inactive porosity can be assumed, which would also explain the initially low hydraulic conductivity. Otherwise, the change in infiltration could be underestimated due to a higher variability, which increases even more following harvesting and requires a larger sample size to provide enough power to the test (Huang et al. 1996). The asymmetric distribution of infiltration data, which is also common in flow-related variables (Watson and Luxmoore 1986, 1988, Wilson et al. 1989, Ankeny et al. 1990, Logsdon and Jaynes 1996), could inflate variance and lead to the underestimation of effects if analyzed on untransformed data.

The skidder traffic reduced infiltration rate by 43 to 61%, while the corresponding increase in bulk density was only 5 to 9%. According to Poiseuille's law, the volume flow is proportional to the fourth power of pore radius. Bulk density, as a function of pore volume, is proportional to squared pore radius. Therefore, the relative change in infiltration should be much larger than in bulk density. Besides, the larger pores are more readily compressed during compaction than smaller pores (Froehlich and McNabb 1984). Such selective reduction in pore space has no effect on the increase in bulk density but it has a large effect on the decrease in infiltration rate as the larger pores transmit most of saturated flux (Warkentin 1971). Pores with effective diameters larger than 500 μm can account for over 60% of the flux in undisturbed soil but less than 20% after skidding (Moore et al. 1986). In the study soils, the analysis of water retention and pore size distribution indicated primary reduction in 30-200 μm pores because these young soils are lacking macroporosity (unpublished data).

Recovery of infiltration in the 3-cycle treatment occurred in two years after skidding (Fig. 2). Similar analysis indicated that soil bulk density in the same treatment remains significantly different from control even in three years after skidding (unpublished data). A complete natural recovery of bulk density of soils compacted during forest harvesting in west central Alberta requires at least a decade (Corns 1988). The possible cause of slow recovery is insufficient soil freezing due to insulating effect of snow maintaining the soil temperature at near-zero point throughout the winter (unpublished data). A somewhat faster recovery of infiltration rate can be explained by a more effective frost action in the very top layer of soil, most impacted during trafficking, and, therefore, serving as a hydrologically limiting layer. Besides, the 9% volume expansion due to frost heave, which could take place in few largest pores at such temperatures (Spaans et al. 1996), could be insignificant when related to the total, largely unfrozen and unchanged volume of smaller pores. The same expansion, occurring uniformly along a large continuous pore, should result in squared (81%) increase in flow, according to Poiseuille's law. Such increase in conductivity of largest pores, which are few but transmitting most of saturated flux, may have had a significant effect on conductivity of bulk soil.

Summary and conclusion

Skidders, equipped with wide tires, do not affect pore space and infiltration of surface soil when operate at soil water potentials below –15 kPa. The 50% reduction in infiltration following skidding on wetter soil will result in intensified lateral redistribution of surface water, which may lead to insufficient moisture recharge on elevations, increased erosion hazard along the down slope skid trails and water-logging hazard in depressions, flat areas and on slopes if skidded across the slope. The number of skidding cycles is not essential in terms of reduction in infiltration rate as most of it occurs right after the first skidding cycle. However, an increase in the number of skidding cycles slows down the recovery of infiltration. After the first three skidding cycles, which represent traffic intensity on the most of an average cut-block, infiltration recovers to a control level within two years. The recovery of infiltration along with reestablishing vegetation should alleviate the most severe water-logging and moisture deficit problems associated with lateral redistribution of surface water. More intensively trafficked trails near decking areas and in the parts of cut-block with limited access will require more time for recovery.

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Table 1. Characteristics of soil and types of equipment

Site	Soil type	Texture	Initial bulk density[z]		Water potential[y]		Machine	Tire (track) width (m)
			5 cm	10 cm	5 cm	10 cm		
			-------------$\mathrm{Mg\ m^{-3}}$------------		--------kPa-------			
1	Orthic/Gleyed Gray Luvisol	Loam	1.13±0.02[x]	1.34±0.04	-14	-15	Skidder	0.8/1.1[w]
2	Gleyed Gray Luvisol	Silt Loam	1.29±0.04[x]	1.37±0.07[x]	-15	-7	Forwarder	0.7
3	Orthic Gray Luvisol	Silt Loam	1.19±0.07[x]	1.31±0.03[x]	-6	-7	Skidder	1.1
4	Orthic Gray Luvisol	Loam	1.21±0.04[x]	1.39±0.03[x]	-9	-6	Skidder	0.8/1.1
5	Brunisolic Gray Luvisol	Loam	1.09±0.06	1.16±0.03	-56	-105	Crawler	0.6
6	Brunisolic Gray Luvisol	Loam	1.08±0.04	1.22±0.02	-29	-29	Skidder	1.1
7	Eluviated Dystric Brunisol	Silt Loam	1.00±0.06[x]	1.25±0.08[x]	-7	-13	Skidder	0.8
8	Orthic/Gleyed Gray Luvisol	Clay Loam	1.15±0.05	1.33±0.07	-41	-37	Skidder	1.1
9	Orthic Gray Luvisol	Silt Loam	1.18±0.09	1.33±0.07	-13	-16	Skidder	1.1
10	Orthic/Gleyed Gray Luvisol	Silt Loam	1.09±0.02[x]	1.17±0.02[x]	-7	-11	Skidder	0.8/1.1
11	Eluviated Dystric Brunisol	Loam	1.01±0.03[x]	1.22±0.06[x]	-7	-9	Skidder	0.8
12	Orthic/Brunisolic Gray Luvisol	Clay Loam	1.07±0.06	1.13±0.07	-90	-19	Skidder	1.1/1.2
13	Gleyed Gray Luvisol	Clay Loam	1.06±0.05[x]	1.24±0.05	-16	-13	Forwarder	1.1
14	Orthic Gray Luvisol	Silt Loam	0.93±0.03	1.12±0.07	-14	-13	Skidder	1.1

[z] Means are followed by standard error of the mean, n=16.

[y] Mean values, n=16 in most cases.

[x] The first 3 skidding cycles caused significant ($P<0.05$) increase in bulk density.

[w] Front/rear if tires are different.

Table 2. Geometric mean infiltration rate by year, site and treatment, n=4

Year	Skid. cycles	Site 1	2	3	4	5	6	7	8	9	10	11	12	13	14
		---x 10^{-6} m s^{-1}---													
0	0	2.7	2.5	6.3	38.9	12.6	18.8	63.3	25.3	1.2	3.0	7.6	7.0		2.5
	3	4.0	0.7	6.5	12.0	10.0	8.6	10.3	7.4	1.5	1.4	7.0	7.4		2.7
	7	2.4	0.5	6.3	7.9	15.0	7.7	7.3	4.8	1.1	3.0	3.0	12.1		3.7
	12	2.1	0.3	3.0	6.8	10.9	6.8	18.7	5.4	0.7	1.5	3.1	13.5		5.4
1	0	9.1	4.4	15.1	29.1	10.7	10.5	32.2	15.9	9.5	6.2		1.8	6.0	6.2
	3	8.9	2.4	15.3	22.6	7.1	15.9	8.9	5.0	7.8	3.5		1.9	5.3	4.9
	7	5.7	2.2	6.6	8.9	7.8	9.8	5.6	9.3	13.4	3.8		5.0	2.9	4.2
	12	3.4	1.7	1.9	12.3	12.1	9.0	0.5	12.6	7.6	1.5		1.9	1.3	3.6
2	0	2.6	7.2		11.9		6.8	10.8	19.1	10.3	14.9				
	3	5.0	5.6	6.7	5.8		8.9	7.2	16.9	5.7	3.7				
	7	4.0	5.7	4.2	1.0		5.2	6.9	9.5	13.2	5.0				
	12	3.1	4.6	2.0	7.6		5.6	2.0	11.7	2.8	4.8				
3	0	6.9	6.8		8.3		15.8	14.8	9.1	8.7					
	3	6.8	5.7		5.1		14.1	7.5	6.7	13.0					
	7	5.2	4.2		5.0		9.5	5.3	3.3	6.4					
	12	7.1	3.3		4.8		7.5	3.9	8.6	5.0					

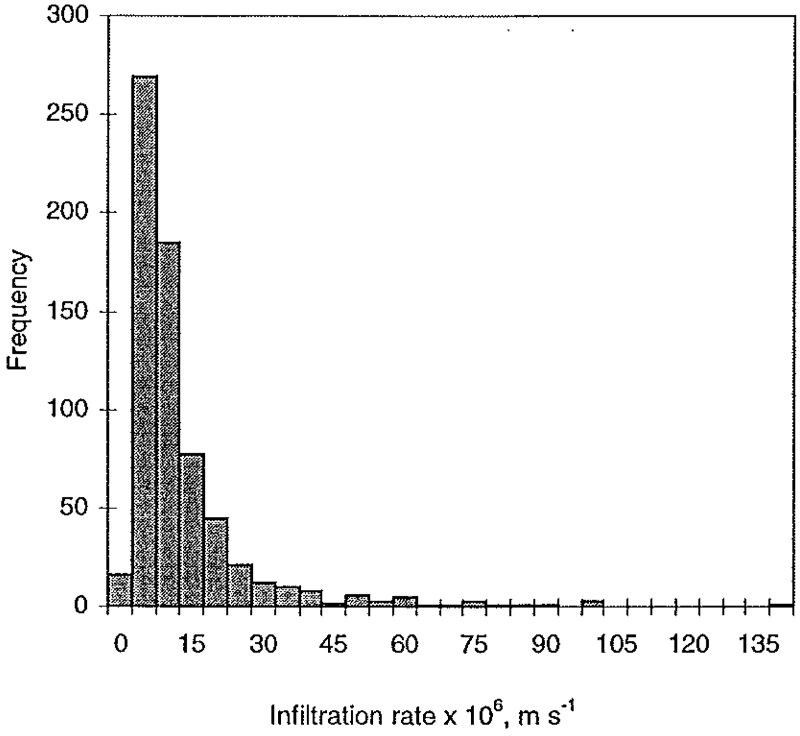
Table 3. Analysis $\log_e$-transformed infiltration data with time as repeated factor

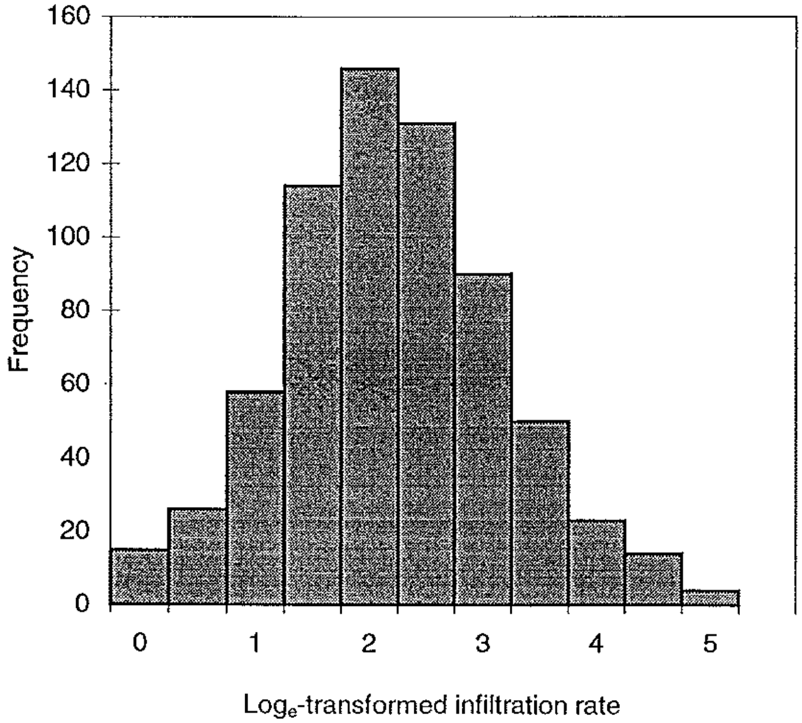
Source of variation	DF	F-value	Pr>F
<u>All sites</u>			
Treatment	3	21.6	0.0001
Year	3	0.4	0.7918
Treatment x Year	9	0.4	0.9124
<u>Compacted sites.</u>			
Treatment	3	25.5	0.0001
Year	3	0.2	0.8846
Treatment x Year	9	0.8	0.5890
<u>Uncompacted sites.</u>			
Treatment	3	2.5	0.0581
Year	3	0.2	0.8680
Treatment x Year	9	1.0	0.4785

List of figures

Figure 1. Distribution histograms of untransformed and $\log_e$-transformed infiltration data.

Figure 2. Infiltration rate relative to control by treatment and year. Different letters indicate significant differences among treatments within a year.


300
250
200
150
100
50
0
Frequency
0
15
30
45
60
75
90
105
120
135
Infiltration rate x 10^6, m s^-1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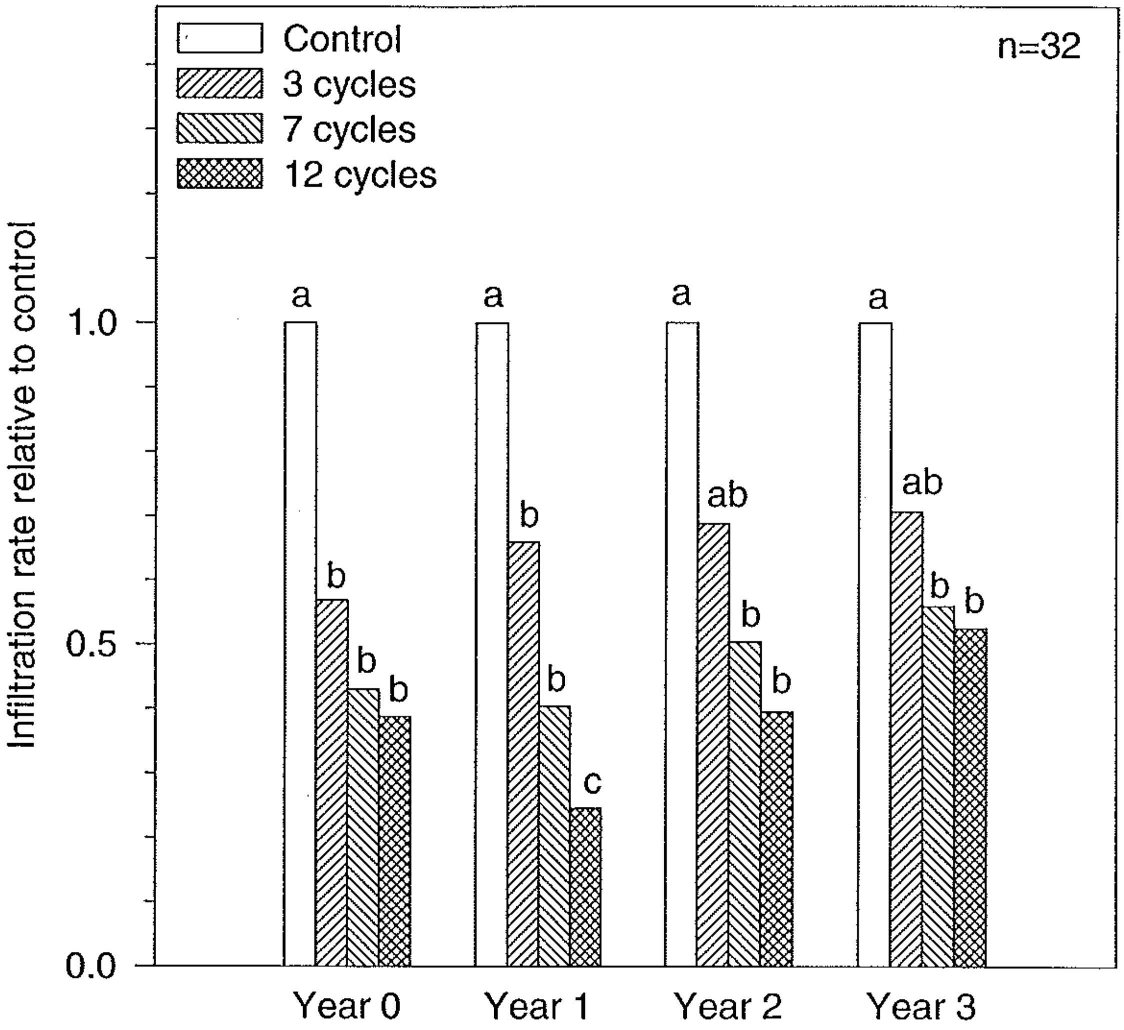
140
120
100
80
60
40
20
0
Frequency
0
1
2
3
4
5
Loge-transformed infiltration rate



Control
3 cycles
7 cycles
12 cycles
n=32
Infiltration rate relative to control
1.0
0.5
0.0
a
b
b
b
a
b
b
c
a
ab
b
b
a
ab
b
b
Year 0
Year 1
Year 2
Year 3