

HARVEST TRAFFIC MONITORING AND SOIL PHYSICAL RESPONSE IN A PINE PLANTATION

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ABSTRACT

Mechanized forest harvest operations induce changes in soil physical properties, which have the potential to impact soil sustainability and forest productivity. The assessment of soil compaction and its spatial variability has been determined previously through the identification and tabulation of visual soil disturbance classes and soil physical changes associated with each disturbance class. This is a time consuming and inaccurate process. The utilization of the GPS provided a means to monitor harvest traffic and transform that information into a detailed map of trafficking. Knowledge of the number of passes (intensity) and their location within the harvest landscape permitted the measurement of soil physical changes in response to the number of machine passes and their spatial structure. Soil bulk density and cone index increased in response to trafficking but the peak values achieved by each varied by sampling time. Soil samples collected immediately after harvest indicated slight response to trafficking but soil samples collected within one year of harvest indicated a greater response, especially in cone index. This was presumably due to differences in soil moisture content at the time of sampling. Spatial structure was evident in the portion of the harvest tract which had less soil moisture. Regardless of temporal differences, bulk density exhibited directional dependence while cone index was isotropic.

Keywords: spatial variability, bulk density, cone index, saturation, loblolly pine, isotropic, anisotropic, GPS, harvest, skidder, feller-buncher.

INTRODUCTION

Mechanized forest harvest operations have induced changes in soil physical properties with the potential to negatively impact soil sustainability and forest productivity. The final compaction status of a harvested site can vary in its intensity and its spatial variability as a result of the interaction between machine and site factors at the time of harvest. The most significant changes have been shown to occur in soil surface layers which can restrict the movement of air and water into soil layers (Hatchell et al., 1970; Gent and Ballard, 1984; Rab, 1994). In the past, information regarding damages related to harvest traffic has required either the identification and tabulation of visual soil disturbance classes throughout the harvest tract, the measurement of changes in soil physical properties in response to harvest traffic, or a combination of the two methods. Both methods were hampered by the significant amount of time and the overall lack of accuracy for true estimates of change in soil physical conditions and its variability within a harvest tract. Recent studies have employed the Global Positioning System (GPS) to collect positional data of trafficking during harvest and then to depict the data as maps of traffic intensities, or the number and distribution of machine passes, to which an area of soil has been subjected (McMahon, 1997; McDonald et al., 1998c). Knowledge of the location of traffic intensities has the potential to provide a means of evaluating soil physical response to trafficking and its variability within a harvest tract (Carter et al., 1999). A fuller understanding of the impact of harvest operations on soil physical changes and its spatial variability can provide information on the location of heavily impacted areas and guide future management decisions related to site preparation and regeneration.

The objectives of this study included the following: 1) examination of the degree of impact associated with a typical harvest operation; 2) evaluation of the relationship between traffic intensity and soil physical response in soil surface layers; and 3) characterization of spatial qualities of two soil physical properties.

MATERIALS AND METHODS

Site and Harvest System Characteristics

The study site was located in a twenty-year old loblolly pine (*Pinus taeda* L.) plantation in Lee County, Alabama and encompassed an area approximately 25.4 ha in size. Tree basal area was estimated to be 27.5 m² ha⁻¹ of loblolly pine and 4.6 m² ha⁻¹ of hardwood with an expected yield of 202.1 Mg (green) ha⁻¹. Soils within the harvest tract classified as fine, kaolinitic, thermic Rhodic Kanhapludults map units and included two slope phases of the Gwinnett series (Soil Conservation Service, 1981). Harvest operations commenced in February 1998 and were completed in March with an average production of approximately 180 Mg (green) per day (7 semi-truck loads per day). The harvest system configuration consisted of a single rubber-tired feller-buncher (HydroAx[†] 511E), two grapple skidders (Timberjack 460D and 450C) pulling to two separate decks, and two loaders (Prentice 270) located at each deck equipped with an integrated delimeter/slasher.

Trafficking Data

Traffic data related to harvest operations were collected by mounting two types of GPS receivers on harvest machinery. A Trimble[†] GeoExplorer II was mounted in the cab of the feller buncher and a Trimble ProXR was mounted in each of the skidders. External antennae were mounted on top of the cabs in their geometric center. Position data were collected in two-second increments throughout the harvest day. Data collected by each GPS unit were differentially corrected in the laboratory and exported to a Geographic Information System (GIS) for final editing. The traffic mapping system transformed point data representing a sampled machine path into a raster map of the number of machine passes. The transformation process involved interpolation of machine movement between sampled positions (linear motion between points was assumed) and subsequent buffering of the interpolated path using a rectangular 'contact' region that represented the path of the machine's tires. When the machine path crossed a point in the raster, its pixel value was incremented. The final result was a raster where each pixel had a value of the cumulative number of machine passes. More detailed information on the transformation of the vector-based trafficking data into raster-based maps has been previously published (McDonald et al., 1998a). The final traffic map had a 0.5 x 0.5 m resolution (0.25 m²) and depicted specific or cumulative totals of traffic intensities and their distribution in the harvest tract.

Traffic Intensities and Soil Physical Response

The impact of traffic intensity on soil physical properties was assessed by measuring changes in soil physical properties at select points which corresponded to estimated traffic intensities within the harvest tract. Two grid point systems were established on either a 6 x 6 m (grid point system 1 – GS1) or 3 x 6 m spacing (grid point system 2 – GS2) in two sections of the harvest tract and encompassed approximately 0.4 ha in GS1 (60 x 73 m) and 0.6 ha in GS2 (73 x 82 m). Each grid point location was geographically referenced by GPS and coordinates were matched to traffic map coordinates to establish a traffic intensity at each grid point location. Soil samples were collected from select grid point locations or *in situ* measurements were made to examine the relationship between traffic intensity and soil physical response. Soil cores approximately 208.4 cm³ in volume were collected from the upper 0.10 m at select grid point locations and analyzed for bulk density (BD) and gravimetric water content (GMC) (Blake and Hartge, 1986). Cone index (CI) data were collected by inserting a Rimik CP20 recording penetrometer to a depth of 0.4 m and collecting penetrometer readings every 0.025 m (ASAE, 1997). Data presented in this paper includes BD and CI measurements of the surface soil layer (0 – 0.1 m) at each grid point location with saturation values (SAT) derived from BD and GMC data. Soil samples were collected from GS1 in Spring 1998 and from GS2 in Winter and Spring 1999.

[†] The use of trade names is for illustrative purposes only and is not intended as an endorsement by the USDA to the exclusion of other manufacturers.

Data Analysis

Mean values and coefficients of variation (CV) for BD, SAT, and CI were computed by the Statistical Analysis System (SAS) (SAS Institute, Cary, North Carolina) for each traffic intensity class except where insufficient number of samples within each traffic intensity were available. In that case, the data were grouped and the means estimated for a range of traffic intensities. Spatially distributed soil physical properties were analyzed with the GS+ Geostatistics package (Gamma Design Software, Plainwell, Michigan) to compute relevant spatial parameters of each dataset and perform point kriging.

RESULTS AND DISCUSSION

Harvest Trafficking

Traffic intensities and their distribution within the harvest tract are depicted in Figure 1. Higher traffic intensities occurred in areas designated as landings and skid trails (6 passes or more), both primary and secondary, and declined as traffic dispersed toward the perimeter of the harvest tract. Traffic intensities of 10 passes or less were recorded by GPS over approximately 95% of the whole harvest tract. Validation of the distribution of traffic intensities in the whole harvest tract was necessary due to the loss of GPS coverage for a complete record of machine movements. The distribution of traffic intensities within the whole tract was compared to a subsection of the harvest tract (5.3 ha) where GPS coverage was complete and the distribution of traffic intensities found to be similar although absolute percentages of each traffic intensity class varied (Figure 2). The distribution of traffic intensities tabulated in GS1 and GS2 agreed with results of the whole tract and subsection with the exception of GS1 in which the one pass traffic intensity displayed the highest percentage (Figure 3).

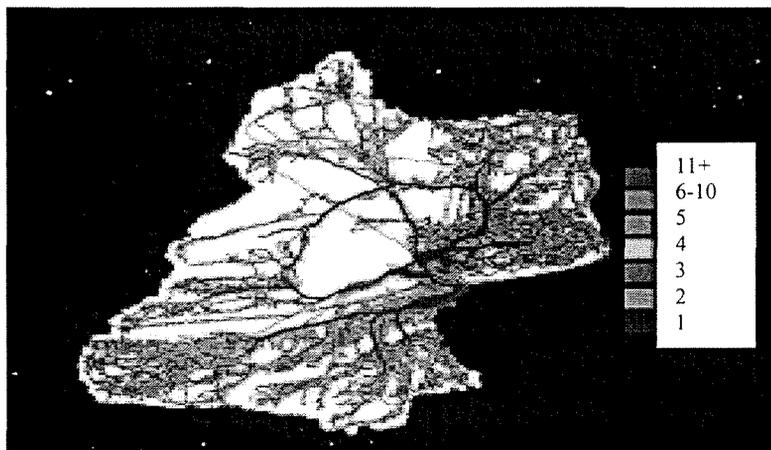


Figure 1. Harvest traffic intensities monitored by GPS in a loblolly pine plantation subjected to a clear-cut harvest, Alabama.

Estimations of the degree and intensity of harvest impacts in the past have relied on the tabulation of surface disturbance classes, a time consuming and less accurate process than the GPS method (Dyrness, 1965; Miller and Sirois, 1986; Aust et al., 1993). Monitoring harvest traffic by GPS yielded information on the intensity and distribution of trafficking throughout the harvest tract as well as a permanent record of traffic related impacts. McDonald et al. (1998b) determined from a comparison of visually assessed traffic disturbances and GPS derived traffic intensities that visual methods overestimated the presence of heavily trafficked areas i.e. skid trails and landings and underestimated undisturbed, or non-trafficked, areas.

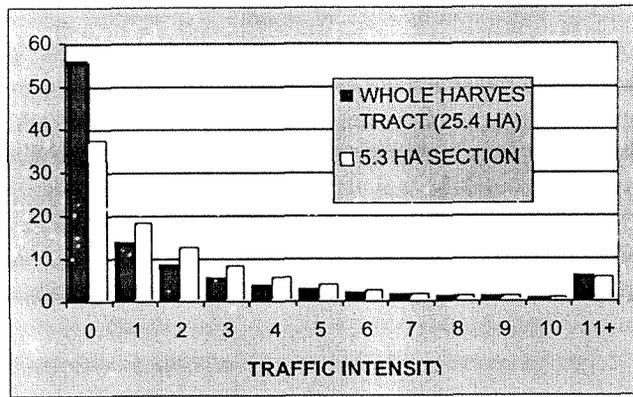


Figure 2. The distribution of traffic intensities (number of machine passes) tabulated over the complete harvest tract (25.4 ha) and a subsection (5.3 ha) of a harvested loblolly pine plantation, Alabama

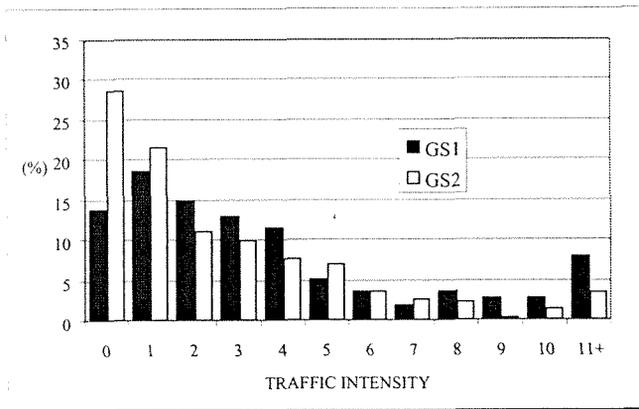


Figure 3. Cumulative frequencies of traffic intensities in two grid point sampling systems in a harvested loblolly pine plantation, Alabama.

Soil Response and Traffic Intensity

Soil physical properties responded to machine trafficking in both grid point systems although the magnitude of response varied (Tables 1 and 2). Bulk density increased in response to trafficking and achieved peak values after three passes in GS1 and after one pass in GS2 and declined with successive machine

Table 1. Means and coefficients of variation (CV) (%) of select soil physical properties of GS1 in response to machine trafficking of the soil surface layer (0-0.10 m) of a harvested loblolly pine plantation, Alabama

<u>Bulk Density</u>				<u>Saturation</u>				<u>Cone Index</u>			
TI †	n ‡	Mean	CV	TI	n	Mean	CV	TI	n	Mean	CV
		(Mg m ⁻³)(%)				(%)	(%)			(MPa)	(%)
0	13	0.98	19.1	0	13	86.0	29.8	0	20	1.23	60.9
1	16	1.01	17.5	1	16	98.2	22.5	1	30	1.60	37.5
2	12	1.10	12.9	2	12	103.4	16.4	2	27	1.42	36.4
3	11	1.13	22.0	3	11	99.0	35.3	3	25	1.50	42.5
4	15	1.09	19.4	4	15	112.3	23.1	4	24	1.51	50.0
5-7	13	1.00	20.3	5	7	101.6	18.2	5-8	28	1.48	50.2
8-24	18	1.10	24.7	6-8	9	105.4	26.5	9-20	25	1.42	36.6
				9-11	9	108.9	26.2				
				12-24	6	89.5	31.5				

† TI = Traffic intensity classes.

‡ n = number of samples.

passes. Cone index response in GS1 was characterized by a peak value after one pass while CI values in GS2 increased with each incremental change in traffic intensity to a peak value at the highest intensity. Differences in water saturation, or the volume of water present in the soil relative to porosity, were noted between the two sites under evaluation. The GS1 saturation values approached or exceeded full saturation while levels in GS2 were substantially lower under all traffic intensity conditions and never exceeded 85%.

Changes in soil physical properties would be expected in response to machine trafficking as a result of reductions in soil volume and a closer proximity of soil particles and aggregates (Greacen and Sands, 1980). The net result of the closer packing of soil particles and aggregates would be a loss of large diameter soil pores essential in the transmission of air and water but an increase in small diameter capillary pores necessary for water storage. This change in porosity is reflected by increased (BD) and (CI) and is a commonly observed in studies of trafficking and soil compaction.

Table 2. Means and coefficients of variation (CV) (%) of select soil physical properties of GS2 in response to machine trafficking in the surface soil layer (0-0.10 m) of a harvested loblolly pine plantation, Alabama.

<u>Bulk Density</u>				<u>Saturation</u>				<u>Cone Index</u>			
TI [†]	n [‡]	Mean	CV	TI	n	Mean	CV	TI	n	Mean	CV
		(Mg m ⁻³) (%)				(%)				(MPa) (%)	
0	30	1.27	20.7	0	30	70.4	42.6	0	98	1.44	33.5
1	25	1.46	18.9	1	25	85.6	36.5	1	73	1.70	30.8
2	9	1.30	14.4	2	9	73.5	28.5	2	36	1.68	28.8
3	8	1.35	27.3	3	8	79.0	27.0	3	35	1.76	30.6
4-5	11	1.27	24.3	4-5	11	79.0	19.2	4	26	1.69	38.6
6-7	9	1.24	20.1	6-7	9	61.2	30.3	5	25	1.79	34.6
8-20	7	1.23	34.0	8-20	7	42.4	43.5	6	14	1.83	27.5
								7-9	17	1.83	38.7
								10-28	16	2.08	20.8

[†] TI = Traffic Intensity classes.

[‡] n = number of samples

Previous investigations of skidder traffic and soil physical property interactions have reported maximum compaction levels after 5 to 11 passes with the final compaction status a reflection of soil and machine properties at the time of compaction (Hatchell et al., 1970; Lenhard, 1986; McNabb and Startsev, 1995; Meek, 1996). Response to trafficking differed between GS1 and GS2 which may reflect differences in soil conditions at the time of sampling rather than conditions at the time of harvest. Sampling in GS1 was conducted in Spring 1998 within one month of the completion of harvest operations when soil moisture status was elevated; GS2 underwent sampling one year later. Soil saturation was nearly 100% in undisturbed locations in GS1 and increased to 100% and higher as traffic intensity increased. Saturation remained well below 85% in all traffic classes in GS2. Soil subjected to external pressures would be expected to increase in soil moisture content through changes in void shape and distribution (Hill and Sumner, 1967; Greacen and Sands, 1980). Bulk density and CI have been observed to exhibit less change under high soil moisture content due to the influence of soil moisture on soil compactibility and pore structure (Hillel, 1980; Thangavadivelu et al., 1994; Sanchez-Giron et al., 1998). Higher soil moisture conditions at the time of compaction in this study would result in a higher soil moisture status due to an increase in capillary pores and subsequent impact to BD and CI would be minimal regardless of the degree of trafficking.

SPATIAL VARIABILITY OF SOIL PROPERTIES

Isotropic and anisotropic semivariogram analyses were performed for BD and CI measurements fitted to an appropriate spatial model and relevant spatial parameters estimated for nugget (C_0), sill ($C + C_0$), range (A_0), nugget semivariance (NS), and model fit (r^2) for each grid point system (Table 3). Spatial parameters were estimated based on a maximum lag distance of 75 m which corresponded to the length of each grid system and lag classes of 3, 6, and 12 m. Spatial parameters for the lag class associated with the best model fit are presented in Table 3. Lag class intervals of 6 m provided the best estimate of spatial parameters with the exception of bulk density under anisotropic analysis.

Spatial dependence was identified for both soil properties in GS1 and GS2 as indicated by the nugget semivariance (NS) values, or the ratio of the nugget (C_0) to the sill ($C + C_0$) value. Nugget semivariances less than 0.25 are an indication of strong spatial dependence, moderate when the ratio is between 0.25 and 0.75, and weak when the NS exceeds 0.75 (Cambardella et al., 1994). An examination of the NS values in GS1 indicate BD and CI had a moderate degree of spatial dependence under both isotropic and anisotropic spatial characterization. In contrast, BD and CI showed strong spatial dependence in GS2 under both types of semivariogram analyses. The spatial qualities of each soil property were best described by the exponential model with the exception of a linear trend in the anisotropic semivariogram analysis of BD in GS1. In both sampling schemes, spatial dependence of BD was best described by anisotropic semivariogram analysis indicative of directional dependence; CI was best described by isotropic semivariogram analysis. Ranges of spatial dependence estimated by the best model fit for each soil variable in GS1 exceeded the limits of the sampling system but were within the limits of the sampling system in GS2.

The utility of each dataset for the preparation of kriged maps was examined through a cross validation process (jackknifing) which compared actual estimates of soil response with predicted values (Table 4). Cross validation statistics generated in the jackknifing procedure indicated a poor model fit and correlation coefficients for BD in GS1 which subsequently improved in GS2. Similarly, kriging a map of CI was better estimated in the conditions associated with GS2. Although the conditions formed in GS2 provided better estimates of the spatial qualities of the harvest tract, the analysis was able to account for a limited amount of the variability. The results of this study appeared to be influenced by conditions at the time of sampling and underscore temporal influences on spatial characterization. The relatively higher degree of spatial dependence of BD and CI in GS2 indicated by NS values less than 0.25 provided better estimates of spatial dependence compared to GS1. Range values estimated from the best model fit for BD (anisotropic) and CI (isotropic) in GS2 were 56.8 (major axis) and 11.4 m, respectively, compared to range values of 280.1 (anisotropic) and 294.9 m (isotropic) in GS1. Long range values detected in spatial analysis coupled with the observation of a linear trend in anisotropic characterization of BD in GS1 are indicative of a lack of spatial structure not detected at the range of sampling (Trangmar et al., 1985). Excess moisture at the time of sampling in GS1 may have contributed to the formation of a relatively uniform soil surface condition with

Table 3. Spatial characteristics of bulk density (BD) and cone index (CI) measurements of the soil surface layer (0-0.1 m) sampled in two grid point systems in a harvested loblolly pine plantation, Alabama

Spatial Parameters	BD		CI	
<u>GS1</u>				
Semivariogram †	Iso	Aniso	Iso	Aniso
Lag Class (m)	12	12	6	6
Model ‡	Exp	Lin	Exp	Exp
Nugget (Co)	0.01	0.04	0.30	0.21
Sill (C + Co)	0.05	0.09	0.73	0.85
Range (Ao) §	10.2	280.1	294.9	250.6
Nugget				
Semivariance ¶	0.26	0.40	0.42	0.25
Model Fit (r ²)	0.11	0.26	0.88	0.44
<u>GS2</u>				
Semivariogram	iso	Aniso	Iso	Aniso
Lag Class (m)	6	6	6	6
Model	Exp	Sph	Sph	Sph
Nugget (Co)	0.01	0.05	0.06	0.001
Sill (C + Co)	0.08	0.27	0.31	0.43
Range (Ao)	13.2	56.3/317.5	11.4	0.01/35.6
Nugget				
Semivariance	0.13	0.20	0.18	0.002
Model Fit (r ²)	0.31	0.55	0.74	0.26

† Semivariogram: Iso = Isotropic; Aniso = Anisotropic.

‡ Model: Exp = Exponential; Lin = Linear; Sph = Spherical.

§ Ranges of anisotropic semivariograms are calculated for major and minor axes of direction and expressed as such except where the values are the same.

¶ Nugget Semivariance = $Co / (C + Co) \times 100$

little difference detected among the sampling locations. As soil moisture decreased throughout the postharvest phase, greater differences in BD and CI in response to variations in traffic intensity became more pronounced and spatial dependence more apparent. Nash et al. (1992) observed longer ranges of spatial dependence of soil moisture in New Mexico rangeland when soil moisture was uniformly distributed. They detected changes in spatial structure and range values (shorter) as soil moisture was depleted by vegetation during the growing season. The longer ranges and linear model fit of BD in GS1 (anisotropic) indicated a lack of spatial structure of the data and reflected the influence of landscape processes rather than harvest traffic (Webster, 1985).

The spatial qualities estimated for BD and CI in GS2 were similar to ranges reported in previous investigations (Webster, 1985; Moolman and Van Huyssteen, 1989; Cambardella et al., 1994; Tsegaye and Hill, 1998). Estimates of spatial dependence for BD have been reported to range between 6 and 129 m while the range of spatial dependence for CI was estimated between 5 and 17 m. It is likely that the wide ranges in spatial dependence previously reported were a reflection of soil conditions and study objectives and do not necessarily permit a direct comparison with the results of this study. However, it is possible that the movement of machine traffic throughout a harvest tract influenced spatial variation of BD and CI to a limited degree and environmental conditions prevalent in the site modified these results.

The usefulness of the sampling schemes under evaluation to distinguish areas of high impact from low are limited due to the high degree of variability associated with the measurements. More potential in the application of spatial statistics might be gained by employing it during pre-harvest assessment of soil conditions to characterize soil properties and predict soil response to trafficking.

Table 4. Regression coefficients (RC) and correlation coefficients (r) of cross validation comparison of predicted versus actual bulk density (BD) and cone index (CI) measurements of the soil surface layer (0-0.1 m) of a harvested loblolly pine plantation, Alabama.

Soil Property	Isotropic		Anisotropic	
	RC	r	RC	r
<u>GS1</u>				
BD	0.03	0.09	0.02	0.07
CI	0.19	0.40	0.21	0.42
<u>GS2</u>				
BD	0.19	0.40	0.20	0.42
CI	0.36	0.53	0.16	0.37

SUMMARY

The use of GPS in monitoring harvest traffic provided the opportunity to prepare maps of traffic intensity and their spatial distribution. The areas of highest impact were associated with landings and skid trails and accounted for approximately 6% of the total harvest tract while areas of 10 passes or less accounted for the remainder. Bulk density and cone index responded to increased traffic intensities and achieved peak values after a limited number of passes. The traffic intensity at which peak values were achieved in response to trafficking varied in each sampling system as well as the absolute value of each soil variable. It is postulated the influence of site conditions at the time of sampling had an impact on the level of soil response and the traffic intensity at which peak values were detected. Spatial dependence was detected in each sampling system but was better defined in the sampling conditions monitored 12 months after harvest. Bulk density exhibited directional spatial dependence while cone index indicated no direction dependence.

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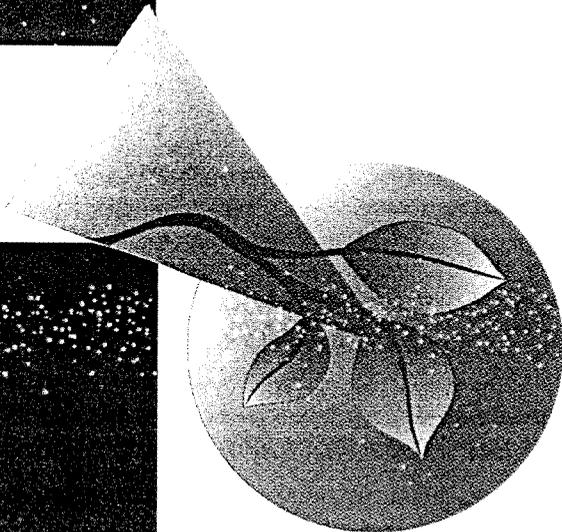
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