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Incorporation of tracers and dazomet by rotary tillers and a spading machine

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Abstract

Soil fumigant efficacy in forest-tree and ornamental nurseries depends on the tillage tool used for incorporation. Maximum depth and uniformity of incorporation of surface applied materials by three rotary tillers and a spading machine were compared in a loamy sand nursery using ceramic-sphere tracers (1–3 mm diameter) and dazomet (tetrahydro-3,5,dimethyl-2H-1,3,5-thiadiazone-2-thione) micro-granules. Depth of incorporation in the top 30 cm of soil was evaluated by (1) recovery of incorporated spheres in 2 cm increments, (2) biocidal activity in 6 cm increments, and (3) cone resistance by 1.5 cm increments to 45 cm. Uniformity of incorporation was evaluated by sphere recovery and biocidal activity. Depths above which more than 95% of the spheres were recovered for the four implements were: 12.5 cm, Kuhn and Fobro rotary tillers; 17 cm, Northwest rotary tiller; 21 cm, Gramegna spading machine. The spading machine produced a distribution of spheres through the soil profile closest to a uniform distribution compared with that produced by the three rotary tillers. Lettuce seed (*Lactuca sativa* L.) germination was inhibited in the upper 12 cm in low and high dazomet rate treatments, indicating that all four implements effectively incorporated dazomet into that zone. Maximum depth (24 cm) for total inhibition of germination was observed for the spading machine regardless of chemical rate. Cone index values showed the following maximum penetration: 14 cm, Fobro rotary tiller; 22 cm, Kuhn and Northwest rotary tillers; 27 cm, spading machine. All three measures of depth show a distinct superiority of the spading machine when the chemical fumigant must reach depths greater than 18 cm. Within transects across the width of the implement, variations of sphere counts among 5 cm^3 volumes were much larger for the rotary tillers than for the spade machine.

Keywords: Pesticide incorporation; Rotary tillers; Spading machine; Fumigation

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1. Introduction

Dazomet (tetrahydro-3,5,dimethyl-2H-1,3,5-thiadiazine-2-thione) is a halogen-free chemical fumigant used in agriculture, horticulture, and forestry for control of soil-borne pests. It is one of several alternative chemical fumigants to methyl bromide (bromomethane), which is considered harmful to the ozone layer. Dazomet has appeal as an environmentally benign fumigant. Methyl bromide was proclaimed harmful to the ozone layer internationally in the Montreal Protocol (US Departments of Agriculture, NAPIAP, 1993). The US Clean Air Act (Section 602) requires that substances identified as ozone-depleting be withdrawn from production, importation, and use by the year 2001 in the USA. Basamid is a commercially available formulation of dazomet that is registered and used in more than 80 countries (BASF Corp., Research Triangle Park, NC). This product is a fine white granular formulation that is normally applied through drop-type spreaders, immediately incorporated into the soil, and then physically sealed into the soil by rolling and applying a water seal or polyethylene tarpaulin. The chemical volatilizes upon contact with soil water to produce several biocidal breakdown products including methyl isothiocyanate.

Dazomet efficacy requires uniform incorporation to a depth appropriate for the target pest and subsequent crop to be protected. Until recently, the BASF Corp. has recommended the use of rotary tillers and disks for uniformly incorporating the product (as per product label). Depth of incorporation needed depends upon the pathogen or pest and the disease to be controlled. The most difficult pests (root diseases caused by *Fusarium* spp. and *Verticillium* spp.) require treatment to a depth of 30 cm and an application rate of 425 kg ha^{-1} (BASF, 1984). Bare-root forest nurseries in the northern USA periodically have serious problems because soil fumigation with dazomet, methyl bromide (bromomethane) + chloropicrin (trichloronitromethane), or metham-sodium (sodium N-methyldithiocarbamate dihydrate) did not adequately control a *Fusarium*-associated root rot of conifers that develops in the second growing season (Juzwik and Rugg, 1996). Reinfestation of pathogens may occur via infested wind-blown soil from headlands or adjacent fields (Vaartaja, 1964), via white pine seed (*Pinus strobus* L.) infested with *Fusarium* spp. (Ocamb and Juzwik, 1993), insufficient injection depth of methyl bromide (Juzwik et al., 1995), or other factors cited by Bloomberg (1985).

Various tracer techniques have been utilized to evaluate tillage implements for incorporation of pesticides (Barrentine, 1987). Tracers used include radioisotopes, common reagents, granules, magnetic particles, and dyes. Fluorescent tracers with photographs have been used most commonly as a qualitative method (Thompson et al., 1994). Dye studies have shown that inadequate incorporation was a major problem for obtaining good weed control with soil incorporated herbicides (Thompson et al., 1994). Staricka et al. (1990) found ceramic spheres to be good tracers for determining vertical distribution of weed seeds following tillage, and stated that the method could be adapted for measuring vertical distribution of surface applied pesticides after their incorporation by tillage implements.

Equipment used for soil incorporation of herbicides includes tandem disk harrows, drag harrows, field cultivators, flexible-shank cultivators, power-driven (PTO; Power Take-Off) tillers, ground-driven tillers, and combination tools (Barrentine, 1987). In comparative trials of these implements, maximum incorporation depth did not exceed 10 cm and uniformity of incorporation varied by equipment. In a forest nursery trial, a tandem disk harrow, a spring tine harrow followed by a serrated roller, a combination of the first two tillage implements, and a power harrow with tines rotating about a vertical axis were evaluated for soil-borne pathogen control and biocidal activity following dazomet incorporation (Kelpas and Campbell, 1994). Incorporation by all implements except the spring tine harrow–roller combination gave complete control of *Pythium* and *Fusarium* spp. to 10 cm depth and only partial control below 10 cm. All treatments apparently moved some dazomet down to 15 cm, and marginally deeper based upon bioassay with radish seed. Incorporation was seriously non-uniform as shown by variations in bioassay results among soil samples at the same depths.

Our objectives were to compare maximum depth and uniformity of incorporation of surface applied materials by three rotary tillers and a spading machine currently used by, or available to, forest nurseries in the USA. Our goal is to find an implement that will give uniform distribution of dazomet granules to 30 cm depth and subsequent control of conifer root disease in bare-root nursery seedlings. In this paper we report on two companion trials conducted in a Wisconsin forest nursery with a loamy sand soil using ceramic sphere tracers and dazomet micro-granules.

2. Materials and methods

2.1. Soils and field sites

Two companion field trials were conducted at the Hayward State Forest Nursery, Hayward, WI, USA (46°00′N, 91°30′W). The soil is a Vilas loamy sand (sandy, mixed, frigid, Entic Haplorthod), containing 87% sand, 10% clay, and 3% silt in the 0–30 cm layer. Other soil properties measured at the site are 1.6% organic C, pH = 5.3 in 0.01 M $CaCl_2$, and a field-capacity water content of 9–11% (w/w). The study fields have been in forest seedling production for at least 45 years. The native soil before intensive cultivation has less than 0.5% organic C in the 0–10 cm layer and a field-capacity water content less than 10% (w/w) in the upper 17 cm.

2.2. Tracing incorporation characteristics with ceramic spheres

Ceramic spheres as tracers were incorporated by four test tillage implements to obtain quantitative information on uniformity and maximum depth of incorporation in the 0–30 cm soil layer. Each tillage implement was randomly assigned to one of five treatment lanes (each 3.7 m × 76 m) within the same field. The first 30 m of each lane was used to establish a consistent and measured tractor speed and to correct tillage implement settings. Fluorescent green or red ceramic spheres (Macrolite™ ceramic spheres, Industrial Mineral Products Division/3M, St. Paul, MN), of 1–3 mm diameter and mean mass of 3.72 mg per sphere, were applied (6.2 beads cm^{-2}) on the raked soil surface of two randomly selected plots (approximately 2 m × 3 m depending on width of assigned tillage implement) in each treatment lane. Tracers were broadcast using a hand operated drop-type spreader (Precision Products, Inc., Springfield, IL). Several passes perpendicular to each other were made over the entire plot to reduce the variability of application. Tracers were applied and tillage was performed on different dates in mid- to late-June 1994. Soil water content was 11% (w/w) in the tillage zone at time of tillage. Three rotary tillers and a spading machine were used at recommended operational tractor ground speeds and PTO revolutions per minute to incorporate the spheres (Table 1). A similar ground speed with some variance owing to prior tillage in the chemical trial field was attained in both trials with the Northwest rotary tiller and the Fobro rotary tiller, but there were differences between trials with the Gramegna spading machine and the Kuhn rotary tiller. These experiment variances will be discussed below. Cone resistance in soil at the time of bead sampling was measured to a depth of 45 cm at a minimum of four positions in each treatment lane with a recording penetrometer (CP-10, Agridry, Rimik Pty. Ltd., Toowoomta, Qld., Australia) having a cone with a base diameter of 12.7 mm and an included semi-angle of 28°. Cone resistance is averaged over 1.5 cm increments. After treatment, the field was watered daily (1.2 cm) for 7 days before sample collection of incorporated spheres.

Soil samples from all plots were taken 1 week after tillage using a tube sampler (Pikul and Allmaras, 1986; Allmaras et al., 1988). Cores were systematically taken using a wooden template, transversely placed (37° offset) across each plot. Sampling holes (19 mm diameter) in the template were 4 cm apart, on center. Depending on operational width of each implement, a minimum of 39 cores (18 mm diameter) were taken to a depth of 30 cm across each transect. Two parallel transects 10 cm apart were sampled for each of two plots in a treatment lane. Each core was sectioned into 2 cm increments and samples were stored in separate paper envelopes until processed. Samples were oven-

Table 1
Specifications of tillage implements and their operation during the tracer and chemical field experiments

Manufacturer and model no. [a]	Tillage apparatus	Working width (cm)	Tractor power (kW)	Trial [b]	Speed		Ground speed ($m s^{-1}$)
					Engine ($rev min^{-1}$)	PTO ($rev min^{-1}$)	
Kuhn EL80N	42 tines of 22 cm length mounted on 7 flanges; tine offset angle of 110°	178	52	tracer	2100	540	0.67
		0.32	0.32	chemical	2100	540	0.31
Fobro Kultipack 1700	60 blades of 22 cm length mounted on 17 flanges; tine offset angle of 151°	170	52	tracer	2100	540	0.32
		0.31	0.31	chemical	2100	540	0.31
Northwest Tiller DHC-96-SC	48 tines of 27 cm length mounted on 8 flanges; tine offset angle of 95°	239	104	tracer	1750	540	0.64
		0.31	0.31	chemical	1750	540	0.81
Gramegna V84/30B	6 spades of 13 cm width by 18 cm length	137	52	tracer	2100	540	0.15
		0.81	0.81	chemical	2100	540	0.32

[a] Kuhn, Fobro, and Northwest rotary tillers all have vertical action, forward rotation with L-shaped tines; Gramegna is a crankshaft type spading machine.
[b] Tracer, when tracer spheres only were incorporated; chemical, when dazomet was incorporated.

dried and broken apart to recover and count spheres. Soil bulk density of the samples was measured but found to be unreliable because large sand grains often prevented sample removal from the tube without some break-up. The total number of spheres recovered per transect was apportioned by their presence in each of the 15 increments in the top 30 cm. Proportional recovery was required because rotary tillers dragged some spheres outside the original site of application. Drag of spheres was not problematic for the moldboard plow, tandem disk harrow, or chisel plow in agronomic applications (Staricka et al., 1990, Staricka et al., 1991).

Statistical analyses consisted of fitting a nonlinear model to the cumulative proportion vs. depth data and using analysis of variance to compare sets of estimated model parameters among tillage implements. Data for transects of the same combination of implement and plot were pooled, owing to their close proximity and lack of independence. The data were fitted using the nonlinear model

$$E(Y) = \left[(1 - \exp(\beta_1 X^{\beta_2})\right]^{\beta_3} \quad (1)$$

where $E(.)$ is statistical expectation, Y is cumulative proportion, X is depth in centimeters, and the βs are parameters to be estimated. The basis for model selection was quality of fit, not biological relevance. Analysis of the residuals indicated no significant lack of fit or heterogeneity of variance. The sets of parameter estimates were compared using the analysis of variance approach outlined by Ratkowsky (1983) with a minor modification to accommodate the multiple plots for each tillage implement. Finally, because F-tests in analyses of variance assume that models are linear in the parameters, simulations as described by Efron and Tibshirani (1993) were conducted to determine the accuracy of significance levels under the null hypothesis of no differences among the tillage implements.

2.3. Tracing incorporation of dazomet using biocidal activity assay

In the second trial, dazomet granules (Basamid™ Granular, BASF Corp.) were incorporated by the same tillage implements as in the first trial and biocidal activity was determined within the 0–30 cm depth. The field for the second trial was divided in half lengthwise (15.5 m × 155.4 m) to accommodate two dazomet rates, 285 kg product ha^{-1} and 570 kg product ha^{-1}. Each tillage implement was randomly assigned to one of four treatment lanes (1.7 m × 155.4 m) established within each half of the field. Dazomet was applied to each half of the field with a tractor-drawn, drop-type spreader (Gandy Co., Owatanna, MN) on 3 August 1994. Immediately after application, each tillage implement was then used to incorporate the chemical in the designated lanes. The same implements were used in the tracer and chemical trials; however, speed was adjusted so that the Kuhn, Fobro and Gramegna implements were operated at the same ground speed (Table 1). The Northwest Tiller was operated at a ground speed faster than the other implements. After dazomet incorporation, the surface soil was compacted with a tractor-pulled roller. Cores for soil samples were taken in a stratified random-sample design. The field length was divided into 26 m lengths, and two of these lengths were randomly selected per traffic lane within each dazomet rate for sampling. Twelve cores of 30 cm length were taken from each selected 26 m linear transect to obtain one of two composited samples. Each core was sectioned into 6 cm increments and composited by depth into clean, wide-mouth, glass jars. Imbibed leaf lettuce (*Lactuca sativa* L. cv. 'Black Seed Simpson') seeds (25 per jar) were placed on the mixed, composited soil and the jars sealed according to standard bioassay procedures (Morton Chemical Co., Chicago, IL). Non-treated soil collected from the field before chemical application was used as a control. Germination of lettuce seed was rated 14 days later based on radicle or hypocotyl–epicotyl emergence.

Cone resistance was measured to a depth of 45 cm in at least four positions in each lane. Before-tillage readings were taken the day before chemical incorporation. Post-tillage readings were taken 7 days after incorporation in the same locations. Binomial rating of lettuce seed germination was recorded for each depth from the duplicate bioassay jars per chemical × implement–treatment lane.

3. Results

3.1. Tracer trial

The eight sets (two plots per each of four treatments) of cumulative proportions (Fig. 1(A)) yielded results for each tillage treatment that were in close agreement. Each proportion was obtained from at least 78 cores each of 2 cm length (two transects with 39 or more cores each). Differences of proportions between plots are generally about 0.05 for the Northwest Tiller, the Kuhn rotary tiller, and the Gramegna spade. Differences of proportion between similarly treated plots for the Fobro were about 0.1 and we cannot explain this observation. The depths above which more than 95% of the spheres were recovered were shallowest for the Kuhn and Fobro rotary tillers and deepest for the Gramegna spading machine (Table 2), based on the fitted model (Fig. 1(B)). The distribution profile by depth for the recovered tracers varied by incorporation implement. These profiles project incorporation depths and clustering by layers in the soil. The spading machine produced a distribution of the spheres throughout the 30 cm profile closest to a uniform distribution compared with that of the three rotary tillers, but all incorporations deviated significantly from a uniform distribution. Analysis of fitted models for each implement yielded similar results.

The model of Eq. (1) adequately described the cumulative proportion vs. depth relationships for all combinations of tillage implement and plot, with a pooled residual standard error $\sigma_{res} = 0.0155$ (Fig. 1(B)). The analyses of variance revealed statistically significant differences among the cumulative proportion vs. depth relationships for the three rotary tillers. The relationship for the Northwest Tiller was different from those for the other two rotary tillers, which were not different from each other. The relationship for the Gramegna spading machine was significantly different from those for the three rotary tillers. The simulations revealed that the actual significance levels associated with the F-test were greater than F-table probabilities. However, the result of significant differences ($P < 0.05$) between the relationships for the Kuhn or Fobro rotary tiller and the Northwest Tiller still held, as did the significant difference ($P < 0.01$) of the relationship for the spading machine. The parameter set estimates (Table 3) illustrate that no one parameter set can be used to characterize the different incorporation patterns of Fig. 1(B).

Cone index measurements were made before and 7 days after the four tillage treatments were applied. Cone indices were similar in the tracer and dazomet trials, and those obtained in the dazomet trial (Fig. 2) are shown as typical. Ground speeds between trials with both the Northwest Tiller and Fobro rotary tiller were similar (Table 1). Even though ground speed between trials was somewhat different for the Gramegna spade machine, the cone index did not differ between trials (not shown). The ground speed differences between trials for the Kuhn rotary tiller did show a more shallow operation (about 2 cm) in the tracer trial as noted in the cone index measurements. Visual observation of ceramic sphere distribution (not shown) for each machine did not indicate any speed or other effects between trials. Measurements of ceramic sphere distribution and cone index vs. ground speed with the Gramegna spade machine in another experiment (not shown) showed no effects up to 0.9 m s^{-1}.

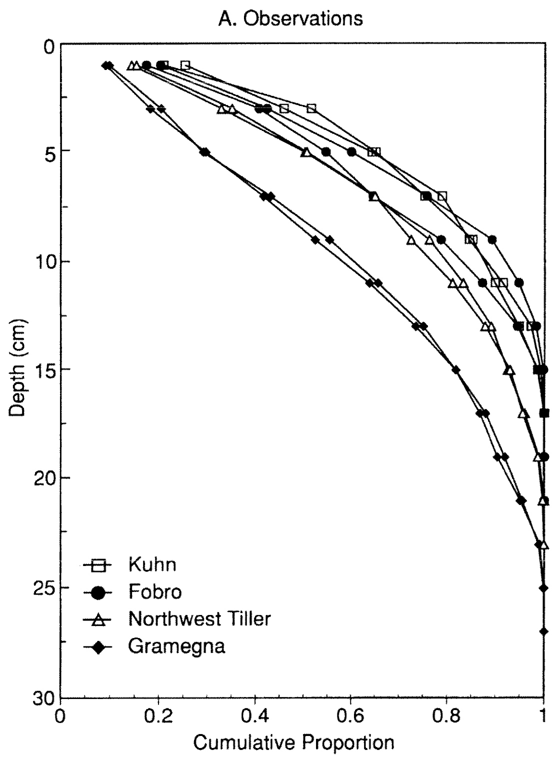

Fig. 1. Cumulative proportion of recovered tracers by depth for each tillage implement: (A) observed data; (B) predictions based on fitted model. For each plot, the observation for each depth is the cumulative proportion by transect × core; predictions were obtained from Eq. (1) with the estimated parameters (Table 3).

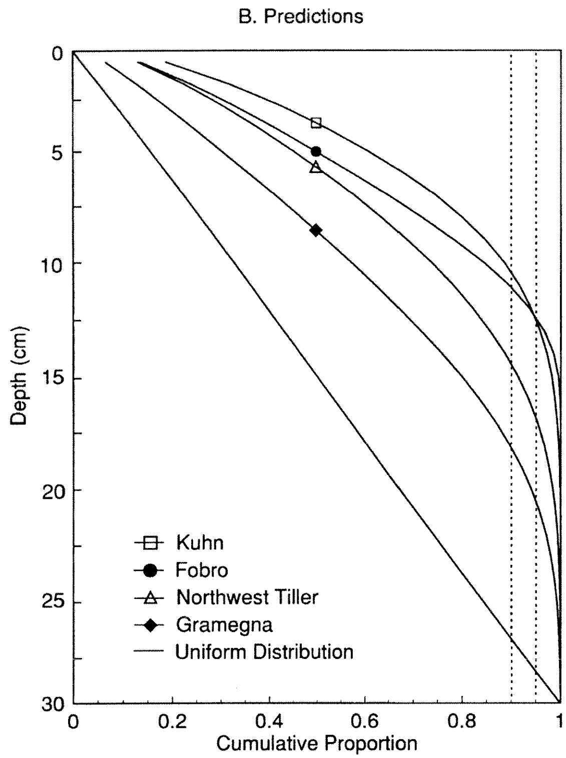

Fig. 1 (continued).

3.2. Dazomet trial

Failed lettuce seed germination in the top two depth increments indicated that all four implements effectively incorporated dazomet to a 12 cm depth in the low and high dazomet rate treatments (Table 4). Germination was either 0% or 100% for all the

Table 2
Maximum depths (cm) of tillage implement penetration as shown by tracers, cone index values, and failed lettuce seed germination in tracer and chemical trials

Tillage implement	Tracer recovery [a]	Cone index values	Lettuce bioassay [b]	
			Low rate [c]	High rate
Kuhn	12.5	22	18	18
Fobro	12.5	14	12	12
Northwest Tiller	17	22	18	18
Gramegna	21	27	24	24

[a] Based on maximum depth at which 95% of tracers are recovered in predicted model.
[b] Based on total inhibition of lettuce seed germination in both replicates.
[c] Refers to rate of chemical application, where low is 285 kg product ha^{-1} and high is 570 kg product ha^{-1}.

Table 3
Tillage implement influence on parameters to estimate the cumulative proportion of beads recovered vs. depth

Implement	Parameters of the regression [a]		
	$\ln(-\beta_1)$	β_2	β_3
Kuhn	−4.711	2.142	0.356
Fobro	−13.061	5.280	0.153
Northwest Tiller	−7.428	2.831	0.275
Gramegna	−10.474	3.645	0.260

[a] Parameters for model given by Eq. (1).

duplicate bioassay jars per chemical × implement–treatment lane at each. Depth for total inhibition of lettuce seed germination was greatest (24 cm) for the Gramegna spading machine (Table 2), regardless of chemical rate. Partial biocidal activity (i.e. one replicate with 100% germination and the other with 0%) was obtained in the 24–30 cm depth where the spading machine incorporated the $570\,kg\,ha^{-1}$ dazomet treatment. Depth of inhibition was shallowest for the Fobro tiller and intermediate for the other rotary tillers.

Cone indices before and after tillage were nearly identical below 30 cm when the surface reference was assumed to be raised 30 mm by the tillage operation (Fig. 2). Consequently, two near-surface readings (each a 15 mm increment) were deleted in the graphical representations of the cone indices after tillage and the two deepest readings were deleted from the pre-tillage measurements. The coefficient of variation for the

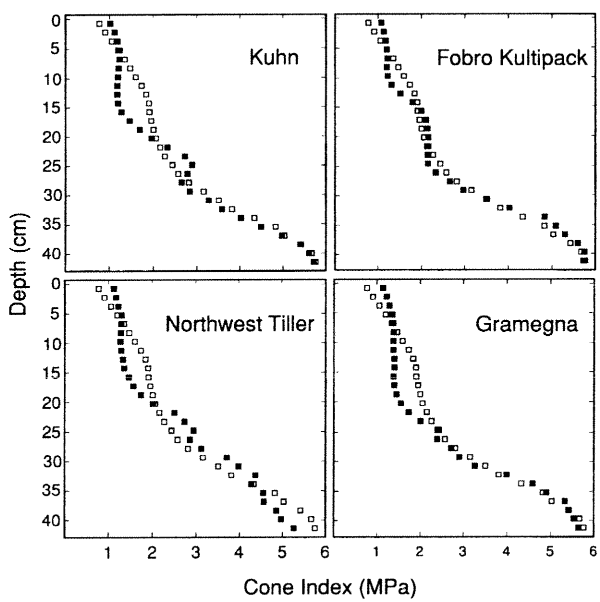

Fig. 2. Cone index measured before tillage and 7 days after chemical incorporation using four different tillage implements. □, Pre-tillage measurements; ■, post-tillage measurements.

Table 4
Tillage implement influence on lettuce seed germination in dazomet treated soil taken at five depth increments to 30 cm [a]

Depth increment (cm)	Chemical rate ($kg ha^{-1}$)	Tillage implement			
		Kuhn	Fobro	Northwest	Gramegna
0–6	285	– [b]	–	–	–
	570	–	–	–	–
6–12	285	–	–	–	–
	570	–	–	–	–
12–18	285	–	+ +	–	–
	570	–	- +	–	–
18–24	285	- +	+ +	- +	–
	570	+ +	+ +	- +	–
24–30	285	+ +	+ +	+ +	+ +
	570	+ +	+ +	+ +	- +

[a] Control soil samples were taken diagonally across the study field 1 day before chemical application and yielded lettuce seed germination in both replicates for all depth increments.
[b] Results of two replicates reported: –, no germination in either replicate; - +, germination in one replicate but not the other; + +, germination in both replicates.

mean values in Fig. 2 remained below 4% above 24 cm and then increased to a maximum of 8% in the 24–45 cm depth. All cone index values were about 3 MPa at 30 cm and increased about 0.2 $MPa\,cm^{-1}$; major changes in organic C and soil color change indicated that 30 cm was the maximum depth of disturbance during the management of these bare-root nursery fields.

Cone index values showed the maximum depths of penetration during the tillage trials to be less than 30 cm (Fig. 2). Maximum penetration (based on cone index) was shallowest for the Fobro tiller, intermediate for the Kuhn and Northwest Tillers, and greatest for the spading machine (Table 2). The Kuhn and Northwest rotary tillers both produced a distinct tillage pan about 7 cm thick. Cone index values did not indicate tillage pans with the Fobro rotary tiller and Gramegna spading machine. All post tillage cone indices showed a compact zone above 4 cm, which was produced by a roller packer commonly used to seal the soil surface during fumigation. Of the three measures of disturbance depth, the cone index change owing to tillage was deeper than measured biocide activity and implied activity measured with sphere recovery (Table 2). Except for the Kuhn rotary tiller, depths for the 95% recovery and measured biocide effect were within 3 cm of each other. The Kuhn rotary tiller did not penetrate as deeply in the tracer trial where the ground speed was faster (Table 1) than in the chemical trial. The mean of two measures of fumigant depth (biocide in Table 4 and the depth where 95% of the spheres were buried in Fig. 1(B)) varied from 2 to 7 cm less than the maximum depth of machine operation.

4. Discussion and conclusions

All three measures of depth show a distinct superiority of the Gramegna spading machine when the fumigant must reach depths greater than 18 cm to reach the target pest organism. Depth of machine operation and associated dazomet incorporation is a critical feature for fumigant activity, especially when soil is infested with root disease pathogens. When an adequate depth of fumigant has been achieved, the material may still not be effective because of a clustered distribution. Both *Fusarium* spp. and *Cylindrocladium* spp., causal organisms of conifer and hardwood seedling root rots, were found by the first two authors in all 6 cm depth increments down to 30 cm in soil samples collected before dazomet incorporation in the second trial field. With all machines the disturbance (cone index change owing to tillage) was deeper than measured biocide and implied activity measured with sphere recovery (Table 2). Except for the Kuhn rotary tiller, depths for the 95% sphere recovery and measured biocide effect were within 3 cm of each other. Comparative cone index indicated a more shallow operation of the Kuhn rotary tiller in the tracer trial. However, the depth differential between measured disturbance and the mean of two measures of fumigant depth varied from 2 to 7 cm. Although the penetrometer characterized disturbance especially well in the loamy sand, it cannot be a good measure of depth of fumigant incorporation.

Tracer trial results show superiority of the Gramegna spading machine in achieving the closest to a uniform distribution of surface applied material from 0 to 30 cm. Preliminary analyses (not shown) from the soil cores spaced 4 cm apart in a transect across the tilled strip show that all four tillage implements produced sphere clusters somewhat corresponding to the spacing of flanges on the rotating drum of the rotary tillers and the spacing of spades on the spading machine (Table 1). The large number of cores used to measure the depth of spheres and dazomet avoided the problem of non-uniform horizontal distribution as noted by Kelpas and Campbell (1994). Nonetheless, sphere count in soil cores, each of 2 cm length and 1.8 cm diameter, used to generate Table 3 had an approximate coefficient of variation of 160% and the standard deviations were a linear function of the sphere count vs. depth data. Such a large coefficient of variation was noted in measures of incorporated crop residue or spheres (Staricka et al., 1991) and pathogen biocide (Kelpas and Campbell, 1994).

Product information (BASF, 1984) and other literature (e.g. Munnecke and Martin, 1964; Munnecke and Van Gundy, 1979) link fumigant activity to soil temperature. They also suggest a moderate water content so that the most biocidally active breakdown product (gaseous methyl isothiocyanate) can diffuse throughout the soil, cautions to use prior tillage for a fine granular soil tilth, and suggest that organic matter or particles reduce efficacy of the fumigant. These conditional requirements, some derived from laboratory soil studies (Smelt and Leistra, 1974), suggest that clustering of dazomet granules may play a major role in failure to achieve pathogen mortality. Laboratory studies may not account for other conditional requirements for best fumigant activity, such as sufficient depth within the Ap layer.

Further spatial analysis of the incorporated spheres is in progress to describe how the three-dimensional clustering of granules may be controlled by these tillage implements. Visual observation during sampling suggests that packing voids or residue debris did not control sphere distribution as was noted for crop residue in other studies (Staricka et al., 1991).

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