

Advances in Soil Science

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Advances in Soil Science

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Preface

The key to sustaining the soil resource base is to maintain, or enhance, soil quality. Soil quality cannot be seen or measured directly from the soil alone but is inferred from soil characteristics and soil behavior under defined conditions. In essence, the quality of soils is analogous to the health of humans, and just as there is no single characteristic that can be measured to quantify a person's health, there is no single measurement that can quantify soil quality. However, there are certain characteristics, particularly when considered together, that are good indicators. Soil quality, just as human health, can be maintained or enhanced by good management practices; and seriously degraded—sometimes irreversibly—with poor practices.

Soil quality is also important because it has direct and indirect effects on air quality and water quality. While the enhancement of soil quality does not always assure parallel improvements in the quality of air and, particularly, water resources, this is often the case. However, soil degradation is invariably accompanied by degraded qualities of both air and water resources.

The consensus among many scientists is that the greatest challenge is not increasing production, but preventing serious deterioration of the soil and water resource base so that the production level can be sustained. Soil degradation is a complex phenomenon produced by a strong interaction between socioeconomic and biophysical factors, which today include the effects of increasing population, a fragile economy, and dismal farm policies, as well as the fragility of soil itself and the harshness of climate. Soil degradation can be subtle and slow until a certain threshold is reached, and then it deteriorates rapidly.

Advances in Soil Science provides a forum for leading scientists to analyze and summarize the available information on a topic, assessing its importance and identifying additional research needs. Most importantly,

contributors are asked to develop principles that have practical applications to both developing and developed agriculture. *Advances in Soil Science* was formulated to be international in scope and cover all subjects relating to soil science. This volume certainly fulfills those goals in that authors are from Denmark, the Philippines, New Zealand, India, United States, and Australia; and the topics cover organic matter, green manures, legumes, soil water repellency, and statistics.

The reception of *Advances in Soil Science* by both authors and readers has been very gratifying. I want to thank the the authors for their excellent contributions, the Editorial Board for their help in selecting such competent contributors, and the Springer-Verlag staff for their kind and efficient assistance. Last, and most important, I want to thank the readers for their acceptance and use of *Advances in Soil Science*.

B.A. Stewart

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Physical Fractionation of Soil and Organic Matter in Primary Particle Size and Density Separates

Bent T. Christensen

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I. Introduction

A. Soil Organic Matter (SOM)

The soil organic matter (SOM) pool encompasses plant, animal, and microbial residues in all stages of decay and a diversity of heterogeneous organic substances intimately associated with inorganic soil components. The soil microbiota and fine roots may also be considered part of the SOM pool. The turnover of the different SOM components varies continuously due to the complex interaction of biological, chemical, and physical processes in soil. The complexity of SOM and its importance to soil fertility have challenged generations of soil scientists, and numerous studies, of which some date back more than two centuries (see historical review in Kononova, 1961), have covered a vast array of aspects of SOM.

Different SOM concepts have prevailed in different historical periods, and, accordingly, methods used in SOM research have developed under the influence of very diverse scientific disciplines. However, chemical disciplines have historically had the most apparent impact on the methodology applied in SOM research, and much experimental and theoretical effort has been allocated to studies on the chemical structure of SOM. The functional aspects of SOM have traditionally been explored by scientists associated with agricultural research, because SOM plays a key role in soil productivity. Knowledge about the nature and turnover of SOM is a prerequisite for understanding the structure, chemical reactivity, and inherent fertility of soils, and for predicting the fate of mineral fertilizers, animal manure, and crop residues added to soil.

Various aspects of SOM have been reviewed regularly in recent years (e.g., Swift et al., 1979; Jenkinson and Ladd, 1981; Stotzky and Burns, 1982; Tisdall and Oades, 1982; Vaughan and Malcolm, 1985; Huang and Schnitzer, 1986; Oades, 1989; Paul and Clark, 1989), and SOM has been in focus at many seminars (e.g., IAEA, 1977; Tinsley and Darbyshire, 1984; Jensen et al., 1986; Cooley, 1987; Coleman et al., 1989). It appears that chemical aspects of SOM and microbially mediated processes are especially well covered. In contrast, reviews of SOM research based on physical soil fractionation and organomineral complexes occupy a much less prominent position.

Throughout most of the history of SOM research, it has been recognized that the interaction of SOM with clay minerals is crucial to SOM behavior (Greenland, 1965a, 1965b; Huang and Schnitzer, 1986). A number of studies have, for example, addressed the effect of various species of mined clay minerals on SOM stabilization in soils incubated with organic substrates (Allison et al., 1949; Lynch et al., 1956; Sørensen, 1967, 1972), but due to the complexity of organomineral associations and the lack of adequate methods, the organic and the mineral parts of soils have most often been treated in separate studies. The mineral part

has been studied by mineralogists after careful removal of SOM, while organic chemists studying various SOM extracts have struggled to minimize the ash content.

B. Physical Fractionation of Soils

Before 1960, relatively few studies had addressed the interaction between SOM and soil minerals directly by attempting to isolate naturally occurring primary organomineral complexes. This is in contrast to the large number of studies on aggregates, which in the present context may be termed secondary organomineral complexes. Although dispersion of soils by shaking with water was used to isolate primary organomineral-size separates, it was realized that simple shaking in water would not ensure a complete disintegration of microaggregates. Size separates obtained after limited dispersion may not represent the soil fraction which the results are intended to refer to. The recovered fraction may contain only the most easily dispersed part of the entire size fraction, causing a selective isolation of SOM. Furthermore, the recovered size fraction may consist of an unknown mixture of primary particles and microaggregates of the same size but made up of particles belonging to smaller size classes. The major progress in the study of primary organomineral complexes was to devise soil dispersion techniques that would allow a quantitative isolation of size and density separates without major effects on the configuration and biological properties of SOM.

The most significant single factor affecting this progress was the application of ultrasonic vibrations in soil dispersion. The use of ultrasonic vibrations for dispersion of soils dates back to 1923 (see review by Watson, 1971), but the studies of Edwards and Bremner (1967) and Ford et al. (1969), and the review by Watson (1971) appear to be the most important milestones, triggering a dramatic increase in the number of studies on natural soil organomineral complexes.

The concept behind physical fractionation of soil emphasizes the role of soil minerals in SOM stabilization and turnover. The physical fractionation techniques are considered chemically less destructive, and the results obtained from physical soil fractions are anticipated to relate more directly to the structure and function of SOM *in situ*.

This contribution considers physical fractionation of soils and its use in SOM studies. Physical fractionation includes density and size separation of primary organomineral particles in whole soil. Thus, aggregates (secondary organomineral complexes) and aggregation will not be considered. Various aspects of physical soil fractionation in relation to SOM studies have been included in the papers by Tiessen et al. (1984b), Christensen (1985, 1987b), Oades (1989), Stevenson et al. (1989), and Elliott and Cambardella (1991), but the methods used in physical soil fractionation have not been reviewed in detail.

Density fractionation is applied to isolate SOM which is not firmly associated with the mineral part of the soil. Soil is dispersed in heavy organic liquids or inorganic salt solutions with specific densities typically ranging from 1.6 to 2.2 g/ml. The light fraction is taken to be less decomposed plant and animal residues, whereas the sediment (or heavy fraction) is expected to encompass "true" organomineral complexes in which SOM is more processed.

Particle size fractionation is based on the concept that SOM fractions associated with particles of different size (and therefore also of different mineralogical composition) differ in structure and function, and therefore play different roles in SOM turnover. Size fractionation may be applied to whole soil samples or to heavy fractions following density fractionation. Soil is usually dispersed in water, the fraction $>63\ \mu\text{m}$ being recovered and further separated by wet or dry sieving. Organomineral complexes $<63\ \mu\text{m}$ are isolated by gravity sedimentation in water, and the $<2\ \mu\text{m}$ fraction may be subdivided by centrifugation. Size separates are occasionally exposed to subsequent density fractionation.

II. Soil Fractionation Methodology

The effectiveness of soil dispersion procedures is crucial for density as well as particle size fractionation. In standard methods of analysis of soil particle size distribution, samples may be exposed to chemical pretreatments in order to remove SOM, sesquioxides, and carbonates, and other cementing agents before being dispersed by a combination of chemical and physical means (Gee and Bauder, 1986). Chemical dispersion treatments are not considered feasible for isolation of intact organomineral complexes, although some studies have applied SOM extractions or included chemicals at various stages of the dispersion procedure (Kyuma et al., 1969; McGill and Paul, 1976; Ladd et al., 1977a; Paul and McGill, 1977; Busacca et al., 1984; Balesdent et al., 1987; Vitorello et al., 1989).

Most studies on organomineral complexes have relied on ultrasonic vibrations to accomplish soil dispersion, but alternative physical procedures have also been employed (e.g., shaking and resins). A number of studies have combined shaking and ultrasonic treatments (Ladd et al., 1977a; Adams, 1982; Balesdent et al., 1987). While standard methods of particle size analysis have been subject to detailed evaluations, procedures used for isolation of intact organomineral complexes have received less attention. This is especially true for techniques used in density fractionation. Soil dispersion methodology will therefore be discussed in relation to isolation of size separates. The rather limited information on dispersion procedures used in density fractionation will be treated in Section II.C.

A. Ultrasonic Dispersion of Soil

Ultrasound, its chemical, physical, and biological effects, and the mechanisms behind acoustic cavitation have been reviewed in detail by Suslick (1988a). The review considers sonochemistry, and industrial, biological, and clinical applications, but reference to soil studies is not included.

Early information on ultrasonic dispersion of soils was reviewed by Watson (1971). The use of ultrasonic vibrations for soil dispersion dates back more than 50 years, but it was not until the beginning of the 1960s that soil dispersion by ultrasonics began to be studied more intensively. During this period much work focused on the use of tank-type ultrasonic disintegrators.

1. Instrument Features

A range of different tank-type vibrators operating at different frequencies has been tested by various workers (Barkoff, 1960; Edwards and Bremner, 1967; Saly, 1967; Bourget, 1968; Parasher and Lowe, 1970; Genrich and Bremner, 1972a). Tank-type ultrasonic vibrators were found to be inefficient for soil dispersion in water even when prolonged treatments were applied. Satisfactory dispersion could be achieved after relatively short treatment periods if a peptizing agent (e.g., Calgon) was added to the soil suspension. In contrast, Edwards and Bremner (1964, 1967) tested sonic (9 kHz) sample-cup and ultrasonic (18 to 20 kHz) probe-type disintegrators and reported that a complete dispersion could be obtained for a range of soils without the use of any oxidants or peptizers. This observation was subsequently confirmed (Watson, 1970; Elonon, 1971; Emerson, 1971), although Emerson (1971) found that some soils showed flocculation of clay particles shortly after dispersion.

Genrich and Bremner (1972a) compared tank-type and probe-type disintegrators. Tank-type ultrasonic equipment did not provide a complete dispersion of soil in water, neither when the soil solutions were vibrated directly in the tank nor when they were kept in flasks and immersed into the water-filled transducer tank. It has been noted, however, (Pritchard, 1974; Suslick, 1988b) that in order to obtain effective dispersion with tank-type vibrators, the position of the sample vessel and the depth of liquid in the tank in relation to equipment frequency are of critical importance. A substantial spatial variability in cavitation intensity produced by tank-type ultrasonic vibrators was clearly indicated by Weissler and Hine (1962). They found greatest cavitation intensity in the center of the tank while intensities decreased sharply towards the sides of the tank. Cavitation in tank corners was 100 times lower than in the center. They also observed a declining intensity with increasing time of continuous operation. Reports on studies using tank-type vibrators for

soil dispersion do not, however, indicate whether experimental conditions were optimized, and the importance of reproducible sample positioning and heights of the liquid in the tank and sample flasks was recognized.

Several potential drawbacks (Suslick, 1988b), including the ones mentioned above, cause tank-type ultrasonic vibrators to be viewed as equipment of limited capability for isolation of intact primary organomineral complexes, and following the appearance of the paper by Genrich and Bremner (1972a), soil dispersion studies have almost exclusively relied on probe-type disintegrators.

More recently, Busacca et al. (1984) and Zhang et al. (1988) applied cup-horn ultrasonic disintegrators for dispersion of soils in water. The cup-horn device replaces the probe tip of standard probe-type disintegrators and radiates energy through the base of the container enclosing the soil suspension. Thereby dispersion is achieved without any direct contact between the ultrasonic probe and the sample. This feature may be essential in studies sensitive to contamination by elements shed from the alloy of probe tips. Significant probe wear has been reported for standard probes after prolonged use (Genrich and Bremner, 1972b; Hinds and Lowe, 1980a), and Busacca et al. (1984) found that 15 min of ultrasonic treatment increased the Ti content of silt by 33% due to Ti shed from a conventional probe. The cup-horn configuration is, however, claimed to be sensitive to liquid levels and to shape of reaction vessel (Suslick, 1988b). Also, the acoustic intensities may be lower than for probe-type disintegrators because the vibrating device is not in direct contact with the sample.

The relationship between working frequency of sonic/ultrasonic vibrators and their efficiency in dispersing soils has not been examined in detail. While tank-type disintegrators may operate at widely different frequencies, most probe-type disintegrators now in use operate at 18 to 22 kHz. Working with two tank-type vibrators operating at 20 kHz and 1 MHz, respectively, Saly (1967) concluded that the lower frequency was more efficient in dispersing soils. Edwards and Bremner (1967) found equipment operating at 9 and 18 to 20 kHz to be equally satisfactory if the dispersion procedures of the instruments were optimized individually. A screening of various types of sonic and ultrasonic vibrators showed that common characteristics of vibrators effective in soil dispersion were high power intensity (power input per unit mass of sample treated) and the absence of a transmitting medium (air or liquid) between vibrating mechanisms and soil suspension. Suslick (1988b) indicates that in the range of kHz to a few MHz, frequency is of minor importance for sonochemical reactions to take place as long as the cavitation threshold is reached and the cavitation intensity is adequate.

Excessive erosion of the probe tip has been found to significantly influence the performance of high-intensity probe-type ultrasonic disintegrators (Watson, 1970; Genrich and Bremner, 1972a,b; Hinds and

Lowe, 1980a). Normal probe wear (gray tip surface) is usually detected after only a few hours use, whereas prolonged use may cause significant probe pitting. Genrich and Bremner (1972b) observed a 19% reduction in clay yield when testing a probe, previously exposed to 40 h of use without maintenance. Hinds and Lowe (1980a) employed a probe severely eroded after 70 h of use, and found its energy output reduced by 60%. Although longer treatment times occasionally could compensate for excessive probe wear, regular polishing of the probe tip was recommended in order to prevent probe pitting and to eliminate reductions in energy outputs. Probe tip maintenance is clearly important, and the maintenance procedures recommended in operating manuals should be followed closely.

The performance of probe-type disintegrators in soil dispersion depends heavily on the characteristics of the instrument. Using a cup-horn probe attached to transducers of two different manufacturers, Busacca et al. (1984) found that both the rated power output and treatment time needed to successfully disperse soils differed substantially between instruments. To describe the effective output from ultrasonic vibrators, Saly (1967) suggested the amount of energy dissipated per unit of irradiated area (W/cm^2) as a basic index for exposure conditions. This was challenged by Pritchard (1974), who suggested that the effect produced on standard materials under specified conditions be assessed and used to standardize experimental setups. Genrich and Bremner (1972b) described a calibration method in which the power output of ultrasonic probes was assessed from the radiation pressure exerted by ultrasonic waves when travelling through liquids. The power output was calculated from the difference in the weight of a balance pan with the probe turned on and off. Probe output power has also been estimated from the heat buildup in water exposed to ultrasonics for a given period (North, 1976; Gregorich et al., 1988; Gregorich, 1989; Morra et al., 1991). Probe output power estimated this way was found to be much lower than the rated energy supply displayed by instrument output control. A determination of the "true" probe power output may provide a useful check on the performance of ultrasonic vibrators engaged for longer periods in a particular experimental setup. The significance of this calibration is less obvious for interstudy comparisons because the efficiency of ultrasonic dispersion procedures depends heavily on noninstrument factors, as will be discussed later.

North (1976) tried to estimate the dispersive component of the total amount of energy conveyed from the ultrasonic probe to the soil by using the difference in heat buildup between water and soil suspension. North (1976) claimed that his calibrations enabled a controlled application to soil of a range of known dispersive energies, a point later critically commented upon by Koenigs (1978).

The disruptive effect of ultrasonics is related to the process of cavitation. Cavitation involves three steps: nucleation (bubble formation),

bubble growth, and implosion (bubble collapse). In pure liquids bubbles remain spherical while collapsing, whereas bubbles near a solid surface implode asymmetrically, generating a liquid jet directed at the surface of the solid (Suslick, 1988a). The very high pressure waves released upon cavitation are held responsible for soil dispersion. The visual assessment of cavitation intensity may be used as a guide for choosing the power output of optimum dispersion. Too vigorous cavitation should be avoided as it may cause a buildup of bubbles at the interface between probe tip surface and liquid (bubble shrouding). The ultrasound may become highly attenuated as it passes through this region, and sonification of the bulk of the liquid may become greatly reduced (Atchley and Crum, 1988).

Effective cavitation depends not only on instrumental specifications such as wattage, frequency, probe dimensions, and probe wear, but also on heat buildup in instrument components and on properties of the irradiated solution. Ultrasonic treatments cause heat buildup in the soil solution (Saly, 1967; Chichester, 1969; Watson, 1970; Elonon, 1971; Hinds and Lowe, 1980a), and it is recommended that suspension temperature be kept at ambient levels e.g., by use of water cooling jackets or ice baths. Heat is also formed in the ultrasonic equipment and may reduce probe performance. Heat formation occurs in the transducer which converts the electrical high-frequency signal into mechanical vibrations, and in the probe which focuses and transmits the ultrasonic vibrations to the soil suspension. Although most ultrasonic equipment has built-in cooling fans, it is recommended to leave the ultrasonic instrument to cool off between consecutive treatments (Watson, 1970; Hinds and Lowe, 1980a; Tan and Troth, 1981; Christensen, 1985). Watson (1970) found that clay yields were reduced by 50% when the ultrasonic vibrator was operated continuously. Similarly, Hinds and Lowe (1980a) recorded a 30 to 40% reduction in energy output in successive runs without intervening rest periods.

2. Dispersion Procedures

The outcome of ultrasonic treatments of soils depends on instrument specifications, but also on actual experimental procedures and soil characteristics. To assess the effectiveness of ultrasonic dispersion, the complete experimental setup must therefore be considered as a whole. Table 1 is a compilation of the experimental conditions of 27 studies using probe-type ultrasonic disintegrators for soil dispersion in water. Sample weights range from 5 to 100 g, and vibrated soil volumes vary between 29 and 538 ml. The soil/water ratios were between 1:20 and 1:2.5, and the rated energy supply and vibration periods cover 60 to 600 W and 3 to 30 min, respectively.

Although the effective probe output power remains unknown, it appears that studies applying more than 1500 J/ml often produce ade-

Table 1. Experimental conditions of 27 studies using ultrasonic probe-type disintegrators for dispersion of soil in water. A particle density of 2.6 g/cm³ was used in calculating the volume of soil suspension and amount of energy dissipated per ml of soil suspension

Reference	Soil clay content (%)	Sample weight (g)	Volume of soil suspension (ml)	Soil/water ratio	Vibration period (min)	Rated energy supply (W)	Energy dissipated per ml of soil suspension (J/ml)	Degree of dispersion ^a
Healy and Claridge (1974)	9-24	25	260	1/10	5	75	90	-
Hamblin (1977)	20-45	20	408	1/20	3	250	110	-
Chichester (1969)	38-44	50	519	1/10	15	75	130	?
Ahmed and Oades (1984)	16-47	50	169	1/3	5	80	142	-
Tate and Churchman (1978)	6-26	20	208	1/10	3	180	155	-
Zhang et al. (1988)	15-31	100	438	1/4	15	140	288	-
Turchenek and Oades (1979)	17-46	20	58	1/2.5	5	80	420	+/-
Cheshire and Mundie (1981)	10-15	50	144	1/2.5	15	100	625	?
Baldock et al. (1990)	10	20	58	1/2.5	5	125	650	+
Catroux and Schnitzer (1987)	22	100	538	1/5	15	400	669	-
Anderson et al. (1981)	24-32	20	208	1/10	8	300	695	+
Tiessen and Stewart (1983)	16-65	20	208	1/10	8	300	695	+
Reuter and Leinweber (1988)	1-69	100	288	1/2.5	10	400	832	+/-
Broersma and Lavkulich (1980)	6-16	20	108	1/5	20	80	890	?
Genrich and Bremner (1974)	15-42	60	173	1/2.5	30	100	1040	+
Armour et al. (1990)	6-65	50	219	1/4	15	300	1232	-
Gregorich et al. (1988)	20	15	81	1/5	16	120	1500	+
Christensen (1985)	3-46	30	162	1/5	15	300	1670	+
Angers and Mehuys (1990)	47	40	215	1/5	25	240	1674	-
Elonen (1971)	0-76	10	54	1/5	30	60	2010	+
Hinds and Lowe (1980a)	21-50	25	135	1/5	20	240	2140	+
Edwards and Bremner (1967)	6-75	10	29	1/2.5	20	60	2500	+
Genrich and Bremner (1972a)	8-72	10	29	1/2.5	15	80	2500	+
Tan and Troth (1981)	11-80	25	85	1/3	20	180	2555	?
McKeague (1971)	8-44	40	115	1/2.5	15	400	3120	-
Dong et al. (1983)	16-61	10	34	1/3	15	125	3324	+
Watson and Parsons (1974a)	4-60	25	135	1/5	20	600	5350	+/-

^a Degree of sample dispersion according to reference: adequate (+), incomplete (-), or unknown (?), while +/- indicate that adequate dispersion was achieved for some soils, but not for others. Conventional textural analyses used as standards.

quate soil dispersion but also that these studies occasionally fail to reach complete dispersion. It should be recognized, however, that the degree of dispersion stated in the references may reflect subsequent flocculation of clay particles, and that the dispersion procedure as such may have accomplished a complete dispersion. The stability of ultrasonically dispersed soil solutions is discussed in Section II.A.3.

Soil samples are usually dried and passed through a 2 mm mesh before being exposed to ultrasonic dispersion. Although dried samples are often presoaked before dispersion (Watson, 1970; Watson and Parsons, 1974a; Hamblin, 1977; Hinds and Lowe, 1980a; Tan and Troth, 1981; Dong et al., 1983; Christensen, 1985; Reuter and Leinweber, 1988), the necessity of this step is not clear. Genrich and Bremner (1972a) found increased clay yields when samples were allowed to presoak for 24 h before a 3 min ultrasonic dispersion. When longer ultrasonic treatments were used, no effect of presoaking was observed. Churchman and Tate (1986) found that limited ultrasonic treatments (260 J/ml) produced higher clay contents for field-moist than for air-dry (20°C) subsamples of four grassland soils. For two soils, air-drying produced similar or higher clay contents.

Compared with a soil/water ratio of 1:5, Edwards and Bremner (1967) found reduced clay yields when using ratios of 1:1.7 and 1:2.5. Hinds and Lowe (1980a) noted that clay recoveries were similar for soil/water ratios of 1:5 and 1:10, whereas a ratio of 1:20 produced significantly lower clay recoveries. Similarly, Watson (1970) and Christensen (1985) found insignificant differences in clay and silt yields for ratios between 1:3 and 1:8. A soil/water ratio of 1:5 to 1:10 therefore seems preferable.

Watson (1970) found higher clay yields for 25 g of soil in 125 ml of water than for 50 g in 250 ml. The relationship between soil suspension volume and degree of dispersion is probably related to the time of exposure of microaggregates to zones of intense cavitation. To increase the contact period, stirring of soil suspensions during ultrasonic treatments is often applied (Emerson, 1971; McKeague, 1971; Genrich and Bremner, 1974; Watson and Parsons, 1974a; Turchenek and Oades, 1979; Cheshire and Mundie, 1981; Catroux and Schnitzer, 1987; Armour et al., 1990). The pressure waves created by cavitation may, however, cause sufficient mixing of the soil suspension (North, 1976; Hinds and Lowe, 1980a; Christensen, 1985; Gregorich et al., 1988), and the need for additional mixing is probably related to the volume of the soil suspension, the shape and dimensions of the containers enclosing the soil suspension, and to the intensity of cavitation. It is envisaged that probe tips with small radiating surface areas used in combination with larger volumes of soil suspension will provide less efficient mixing than larger probes used on smaller volumes. As the same factors probably affect the overall intensity of cavitation, probes with relatively large diameters should be used in combination with moderate soil-suspension volumes.

Given the instrument features (probe dimensions, power output intensity) and sample properties (soil type, soil/water ratio, soil-suspension volume), the outcome of ultrasonic dispersion procedures depends on the length of treatment time. Limited ultrasonic treatments provide incompletely dispersed soils, causing microaggregates of smaller size particles to be included in the silt and sand size separates. Excessive treatments may lead to abrasion of primary organomineral complexes (see Section II.A.3).

The influence of ultrasonic treatment time on the degree of soil dispersion has been studied regularly (Edwards and Bremner, 1967; Chichester, 1970; Watson, 1970; Emerson, 1971; Genrich and Bremner, 1972a; North, 1976; Busacca et al., 1984; Christensen, 1985; Gregorich et al., 1988; Morra et al., 1991), and Figure 1 illustrates the basic relationship between clay and silt yields and treatment period. The yield of clay increases and that of silt decreases gradually with increased treatment time, demonstrating that a progressive disruption of silt size aggregates takes place. In accordance with other studies (Edwards and Bremner, 1967; Watson, 1970; Gregorich et al., 1988), the gain in clay exceeds the concomitant loss of silt particles showing that sand size aggregates are being dispersed too. The rate of change in clay and silt yields levels off with increased time of treatment, and after 15 min of ultrasonic treatment yields of clay and silt reach a plateau, indicating that complete dispersion has been achieved. Similar dispersion patterns have been demonstrated in other studies (Edwards and Bremner, 1967; Chichester, 1970; Watson, 1970; Emerson, 1971; North, 1976; Gregorich et al., 1988). It was also observed that treatment times exceeding what was needed for complete dispersion caused but a slight further increase in clay yields. This suggests that a "true" plateau of complete dispersion exists, but also that excessive inputs of ultrasonic energy may lead to further dispersion of strongly cemented microaggregates or to a slow gradual breakdown of primary particles. However, as noted by Edwards and Bremner (1967), the lack of an absolute standard of complete dispersion is an adverse feature which studies of primary organomineral complexes share with conventional textural analyses.

Given an optimized experimental setup, the time of ultrasonic treatment required to achieve complete dispersion will vary between soil types. Ideally, the optimum treatment time should be determined for each soil under study in order to ensure that ultrasonic dispersion is neither too limited nor excessive. Treatment times adopted in practice, however, will have to be tuned to cover a range of different soils.

Table 1 demonstrates that a relatively large number of studies have failed to disperse soils completely. Watson (1971) and North (1976) stressed the lack of standard procedures and indicated that standardization of ultrasonic dispersion methods was desirable. Differences between instrument specifications, and the interaction between soil type and the treatment time required to achieve adequate dispersion do not,